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The cement clinker

Portland **cement** is an important building material binder that hardens with the action of water. Concrete is a mixture of cement, water and fillers such as sand and stones. The cement **clinker** is a coarse agglomerate of synthetic minerals that is produced by burning a **raw meal**, consisting of a selected mixture of raw materials, at very high temperatures in a specialised kiln system. The clinker mostly appears as a dusty granular mixture of dark grey/black particles up to 40 mm in size. The cement product is prepared by grinding the clinker with some gypsum into a fine powder.

The most common way of characterising clinker and raw materials is by a chemical analysis using X-rays giving the content of elements expressed as oxides in percentage. (e.g. CaO: 43,5%, Fe_2O_3: 6,72%).

In cement chemistry the following abbreviations are used for some oxides					
C = CaO	S = SiO_2	A = Al_2O_3	F = Fe_2O_3	T = TiO_2	M = MgO
K = K_2O	N = Na_2O	H = H_2O	$\overline{S}$ = SO_3	P = P_2O_5	F" = FeO

Main clinker minerals

The oxides of **calcium** (C), **silicon** (S), **aluminum** (A) and **iron** (F) are the 4 major components that react to form the main clinker minerals:

C_3S 50-65%	**Alite** hardens faster than C_2S and contributes to early strength formation. C_3S has a high heat of hydration (500 kJ/kg). It is resistant to sulphur attack. High content of C_3S will increase strength at all ages.
C_2S 10-30%	**Belite** hardens slowly and contributes more to late strength development. It is resistant to sulphur attack. It has a low heat of hydration (250 kJ/kg). The content of C_2S in low heat cement used for the castings of large foundations is high.
C_3A 4-10%	**Calcium aluminate** sets quickly and contributes to the early strength but minimally to the final strength. C_3A also has a high heat of hydration liberating a large amount of heat during the first few days of hardening (900 kJ/kg). Cements with low percentages of C_3A are resistant to soil and water containing sulphates. Higher concentrations of C_3A can react with sulphate causing expansion and crack formation exposing more C_3A leading to further penetration of sulphates.
C_4AF 2-10%	**Calcium alumino ferrite** has a minimal effect on the strength of cement, contributing only to the final strengths. C_4AF gives a dark colour to cement and is avoided in the manufacture of white cement.

C_3S and C_2S make up the main part (usually 75-85%) of the clinker and are responsible for most of the strength properties of the cement. C_3A and C_4AF act as melt in the clinker formation process constituting 10-20% of the clinker.

Any lime which has not reacted with silica, alumina, or iron will be left as free CaO. The free oxides of CaO and MgO usually represent less than 5% of the clinker. They are generally unwanted components indicating: insufficient burning of the clinker (CaO), decomposition of C_3S in the clinker or too high lime saturation (LSF) of the clinker.

Modules

The content of the major oxides is controlled by using modulus calculations to maintain the required proportions of CaO, SiO_2, Al_2O_3 and Fe_2O_3. The moduli are calculated as follows:

Parameter	*Formula*	*Typical range*
Lime Saturation Factor	$LSF = \frac{100 \times C}{(2{,}8 \times S + 1{,}18 \times A + 0{,}65 \times F)}$	92-98
Silica Modulus	$MS = \frac{S}{(A + F)}$	2,3-2,7
Alumina Modulus	$MA = \frac{A}{F}$	1,0-2,5

Lime Saturation Factor (LSF)
The Lime Saturation Factor is the ratio of the actual amount of lime to the theoretical lime required by the other major oxides in the raw mix or clinker. When LSF is >100% the ordinary clinker will always contain some free lime. When firing a kiln with coal or other fuels containing ash the LSF of the raw meal can be higher than 100%. The incorporation of ash into the clinker lowers the LSF because of the silica, alumina and iron content of the ash. To monitor the burning process, the amount of unreacted CaO_{free} (free lime) in the clinker is analysed. The lower the free lime the closer the reactions are to completion, however too low free lime can also indicate too hard and uneconomic burning. The free lime target is normally about 0.5-1.5% CaO_{free}. In theory a clinker with LSF ˜ 100% can be burned to 0 % free lime.

Silica Modulus (MS)
The amount of melt phase in the burning zone is a function of MS. When MS is high, the amount of melt is low and vice versa. Therefore, when the MS is too high, the formation of nodules and the chemical reactions may be too slow making it difficult to obtain a satisfactory degree of reaction. The kiln becomes more dusty and difficult to operate. The higher the MS the harder it is to burn. When MS is too low there may be too much melt phase and the coating can become too thick. Recommended step changes 0.05 – 0,1 unit.

Alumina Modulus (MA)
The temperature by which the melt forms depends on the MA. The lowest temperature is obtained when the MA is approximately 1.6 which is the optimum regarding formation of clinker minerals and nodulisation. The MA also affects the colour of the clinker and cement. The higher the MA the lighter the colour of the cement. MA is not always a directly controlled parameter.

Approximated cement mineral composition (calculated using Bogue's formulas)

The true mineral composition is determined by microscopy or x-ray diffraction analysis. An estimate of the clinker mineral composition may be calculated assuming that the major oxides have reacted to the theoretical completion of the models below. The first table of formulas correspond to a model with a mix of C_3S and C_2S. This is the most common model applied.

Model	**C_3S - C_2S - C_3A - C_4AF**
Condition!	**(C - CaO_{free}) < 2,8xS+1,65xA+0,35xF**
C_3S	**= 4,07x(C - CaO_{free}) - 7,6xS - 1,43xF - 6,72xA**
C_2S	**= 2,87xS - 0,75xC_3S**
C_3A	**= 2,65xA - 1,69xF**
C_4AF	**= 3,04xF**
CaO_{free}	**= measured**

The second column corresponds to a model with a theoretical surplus of CaO hence no C_2S remaining:

Model	**CaO_{free} - C_3S - C_3A - C_4AF**
Condition!	**(C - CaO_{free}) > 2,8xS + 1,65xA + 0,35xF**
C_3S	**= 3,80xS**
C_2S	**= 0 (by Model)**
C_3A	**= 2,65xA - 1,69xF**
C_4AF	**= 3,04xF**
CaO_{free}	**= C - 2,8xS - 1,65xA - 0,35xF**

Operational measurements on clinker:

Litre weight: The litre weight of a selected fraction of the clinker product is measured. It is usually the fraction of 5-10 mm or 6-12 mm particles that are sieved and weighed in a cup with fixed volume. The top of the cup is levelled of with a ruler. The measurement in g/l is generally between 1100-1300. The litre weight of a clinker type at a specific plant correlates to free lime when burnability remains constant. Higher temperature generally gives higher litre weight but very high temperatures can lower the litre weight because of dust agglomerates.

Free lime: The free lime measurement is carried out on a representative sample of the clinker product. Generally the free lime is targeted just below 1,5%. Temperature, residence time and burnability influence the achieved free lime level.

Minor components

In addition to the 4 major oxides many other compounds will often be present in the fuels and raw materials and subsequently in the cement clinker. Among these the most common are MgO, K_2O, Na_2O, SO_3. Although the content of such compounds may be small, their presence may greatly affect the operation and the quality of the product.

MgO: (0-5%): Some MgO is built into the clinker minerals. High contents of MgO may cause expansion during hydration. Higher SO_3 in the clinker may stabilise the expansion.

Alkalies: Some of the Na_2O (Sodium oxide) and K_2O (potassium oxide) is built into the clinker minerals C_3A, C_4AF and C_2S. Most of the remaining alkalies will remain water soluble. If the alkalies are not balanced by sulphates they will remain very volatile and can accumulate in the circulation between kiln and preheater. An increased content of water soluble alkalies in the cement tend to increase early strength and reduce late strength. Low alkali cements must have an Na equivalent below 0,6%.

Na (eq) = Na_2O + 0,658 x K_2O

SO_3: Sulphates may be present in the clinker up to about 3%. The sulphates in the clinker come from the fuel and possibly the raw materials. Sulphur in raw materials can increase SO_x emissions and cause build-up in the preheater tower. Sulphate can form a stable compound with Potassium (K_2SO_4) and to a lesser extent Sodium (Na_2SO_4). The alkali sulphates melt at ~880-1100°C and form an early and minor melt phase which can facilitate some of the clinker formation reactions. If burning zone temperatures are high or there are reducing conditions in the kiln the alkali sulphates can become volatile and accumulate in circulation.

Sulphate excess = SO_3-0,85•K_2O-0,65•Na_2O (g/100kg clinker)

Cl: Chlorides form stable compounds with the alkalies and are more volatile than the sulphates. The clinker can contain about 0,012-0,023% Cl. The throughput is limited by the burning zone temperature. About 1% Cl in the hot meal at kiln inlet is generally considered as max. to maintain a good material flow. A bypass can be used to drain chlorides from the kiln system. Some waste fuels contain chloride.

F: Fluoride appears in some raw materials up to about 0,14%. Fluoride can be added as CaF_2 or as a waste material containing F to improve the burnability and reduce clinkering temperature. However from 0,3-0,5% F on clinker basis a reduced activity starts to appear. At Fluor >0,5% retarded setting, reduced early strength and increased late strength may appear.

P_2O_5: Phosphates are present in some raw materials but especially in secondary fuels such as animal/bone meal and household wastes. P_2O_5 content above 0,5-1,0% in the clinker has negative effect on reactivity and setting.

Heavy metals: Increasing attention to presence and toxic effect of heavy metals is motivated by concerns for health and environmental risks.

Hg, Tl, Cd, As, Co, Ni, Se, Te, Sb, Pb, Cr, Cu, Mn, Pt, Rh, V, Sn(Tin), Ag, Ba, Be, Zn.

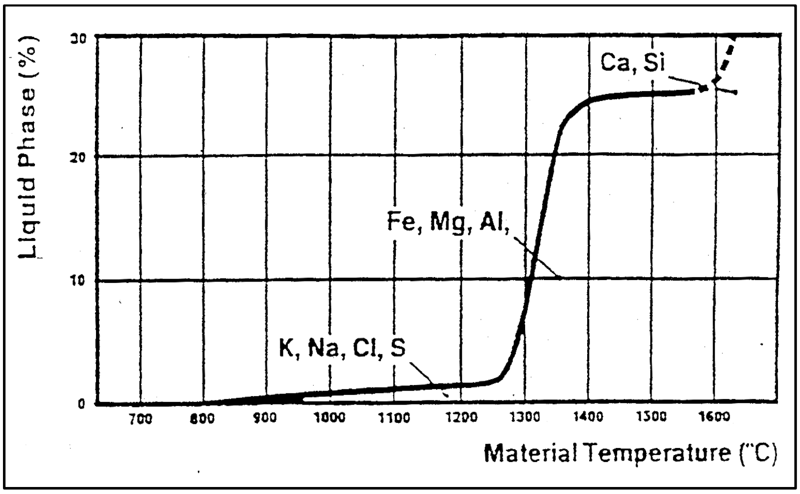
Heavy metals are normally present in small trace amounts in raw materials and fuels. Recycling of waste materials either as fuel into energy or into alternative raw materials demands a higher level of control, knowledge and verification of heavy metal pathways. A global awareness of environment and health issues demand conscientious waste management procedures.

Heavy metals are in some cases reported to have influences on cement quality. For specific evaluations and information contact FLSmidth about waste burning.

Clinker formation

The formation of cement clinker minerals and agglomeration into nodules is enhanced by the presence of a melted **liquid phase**. The melted phase mainly consists of the aluminium-, iron- and magnesium oxides but the alkalis and sulphates also contribute to the melted phase. The “wetting” by the melt enables the transport and contact of reactants and increasing the speed of reaction. The liquid phase also plays an important role in the nodulisation and formation of coating in the kiln. The clinker granulometry (bypassing the crusher) expresses the result of nodulisation (in **N1**).

The main part of the melt phase consisting of aluminates and ferrites appear from 1250°C to ~1400°C. A small liquid phase starts to appear already from 750-1000°C. It consists of minor components mainly alkalies as hydroxides, chlorides or sulphates. This melt often participates in undesirable coatings and build-ups in the lower preheater, kiln inlet area and cooler inlet(snowmen). The melt percentage at 1450 °C can be estimated using the formula below:

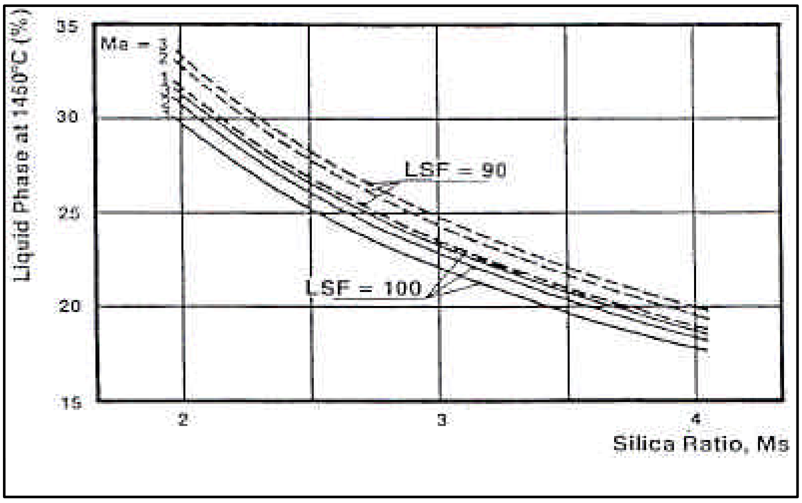


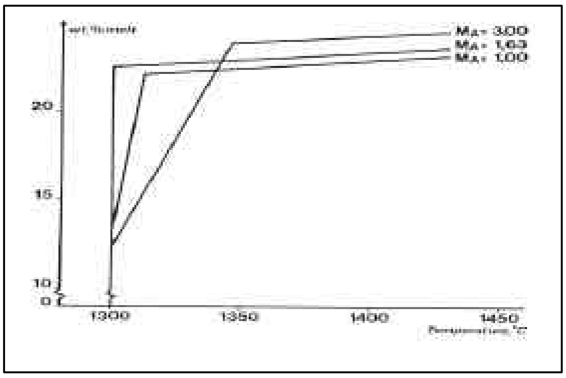
$$0{,}2 < MA < 5{,}0$$

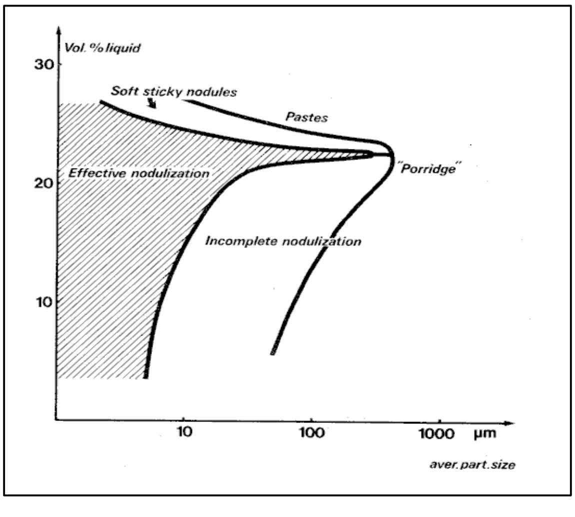
$$\%LIQ\,(1450\ ^{o}C) = 3{,}00 \times A + 2{,}25 \times F + S$$

$$S = MgO + K_2O + Na_2O + SO_3$$

The calculations do not compensate for solid solution of melt components in the cement clinker minerals and therefore the real values will be lower particularly with low liquid amounts.







The normal range of the melt phase is 22-25%. The relation between melt phase, nodulisation, coating and dusty operation is complex. Too much melt may give a coarse and lumpy clinker product. Too little melt, too little burning, too much burning, too much early melt (voltiles), too hard burnability all tend to give a dusty clinker product. *(Keep checks on clinker granulometry and observe if it is affected by changes in chemistry)*.

The melting point of substances in mixture is different and often lower than of the pure substances. As the melt is formed it becomes an active participant in the mineral formation by providing a medium for reactions to take place. The dissolved reactants that achieve contact proceed to form clinker minerals.

The liquid phase continuously changes as the reaction product of clinker minerals crystallise and leave the melt phase while new reactants dissolve and enter the liquid phase. The reactions continue until there are no more reactants available to enter the liquid phase. The cooling at the outlet of the kiln burning zone lowers the reaction rate and ultimately solidifies the melt and stops any further reactions. During initial cooling some reactions may reverse which is why rapid cooling is important. Modern coolers rarely give any significant reversal of reaction.

Influence of modules on liquid phase:

LSF: Reduction of LSF slightly increases the quantity of liquid phase. The influence of a reduction of LSF on the burnability may have a positive effect on nodulisation.

MS: Reduction of MS will increase the quantity of A and F, effectively increasing the quantity of liquid phase. The length of the melting zone will remain the same but the formation of nodules will be more rapid and increase the nodule size and coating thickness.

MA: Influences the temperature at which the melt forms. The lowest temperature of melt formation is with an MA of 1,6. If the melt occurs at higher temperatures the heating zone will lengthen and the melting zone (coating) will shorten.

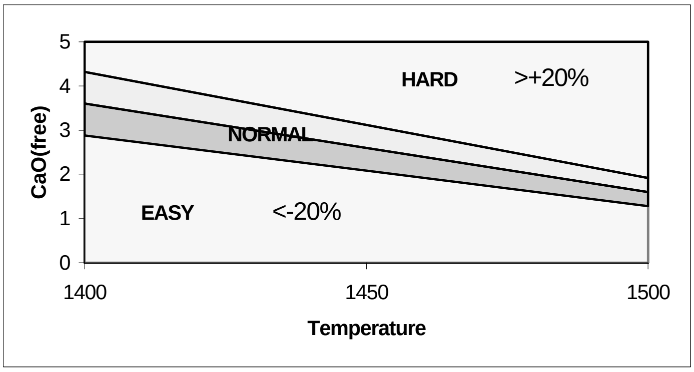
The reaction zones in the kiln system

Drying zone ≤100°C	Evaporation of free water(wet process)	No radiation color
Preheating zone 100-750°C	Evaporation of crystal (bound) water Combustion of pyrite and carbon	Dark red –Cherry red
Calcination zone 750-1000°C	Calcination of carbonates Alkali sulphate melt formation	Cherry red –Orange red
Transition & Burning zone 1000-1500°C	Heating of material Formation of C2S Partial fusion and formation of C3S, evaporation of volatiles	Orange red/yellow – white

The **burnability** of a raw meal is an expression of how difficult it is to burn. The level of unreacted free lime (CaO_{free}) is an indication of incomplete reaction (or an over saturated lime total). Under similar conditions of temperature and residence time the level of free lime will depend only on the physical and chemical characteristics.

The burning conditions in a rotary kiln are different from a laboratory oven. Therefore it is not possible to translate measurements of free lime levels directly. FLS qualifies the burnability measurements in the laboratory, with an index and the descriptive terms, <u>easy</u>, <u>normal</u> and <u>hard</u>

The burnability is measured in the laboratory by placing raw meal samples at 1400°C, 1450°C and 1500°C respectively for 30 minutes and measuring the resulting free lime. The higher the free lime in the samples the more difficult it is to burn and the higher the burnability index.



The FLS burnability is indexed with 100 at the following values 3.6%(1400), 2.6%(1450) and 1.6%(1500). An index value below 80 is Easy, 80-120 is Normal and above 120 is Hard.

ex.: A raw meal burning test has the following results: $\mathbf{CaO_{free}}$(at following temperatures): 3.8%(1400), 3.0%(1450), 2,2%(1500) =>
(3.8/3.6+3.0/2.6+2.2/1.6)*100/3 =
<u>119.5 (Normal/Hard)</u>

The burnability is statistically linked to certain characteristics of the raw meal. Particularly the presence of certain oversized particles, high LSF and MS will impair the burnability and counteract complete reaction.

$$\mathbf{CaO}(1400°C)=0.33x(\mathbf{LSF}-95)+2x(\mathbf{MS}-2,3)+0.93xSiO_2(+45\mu)+0.56xCaCO_3(+125\mu)$$

Particles of calcite $CaCO_3$(+125μ) and quartz SiO_2(+45μ) are determined by microscopy.

A **Plant specific formula** can be determined using methods more available at plant laboratories:

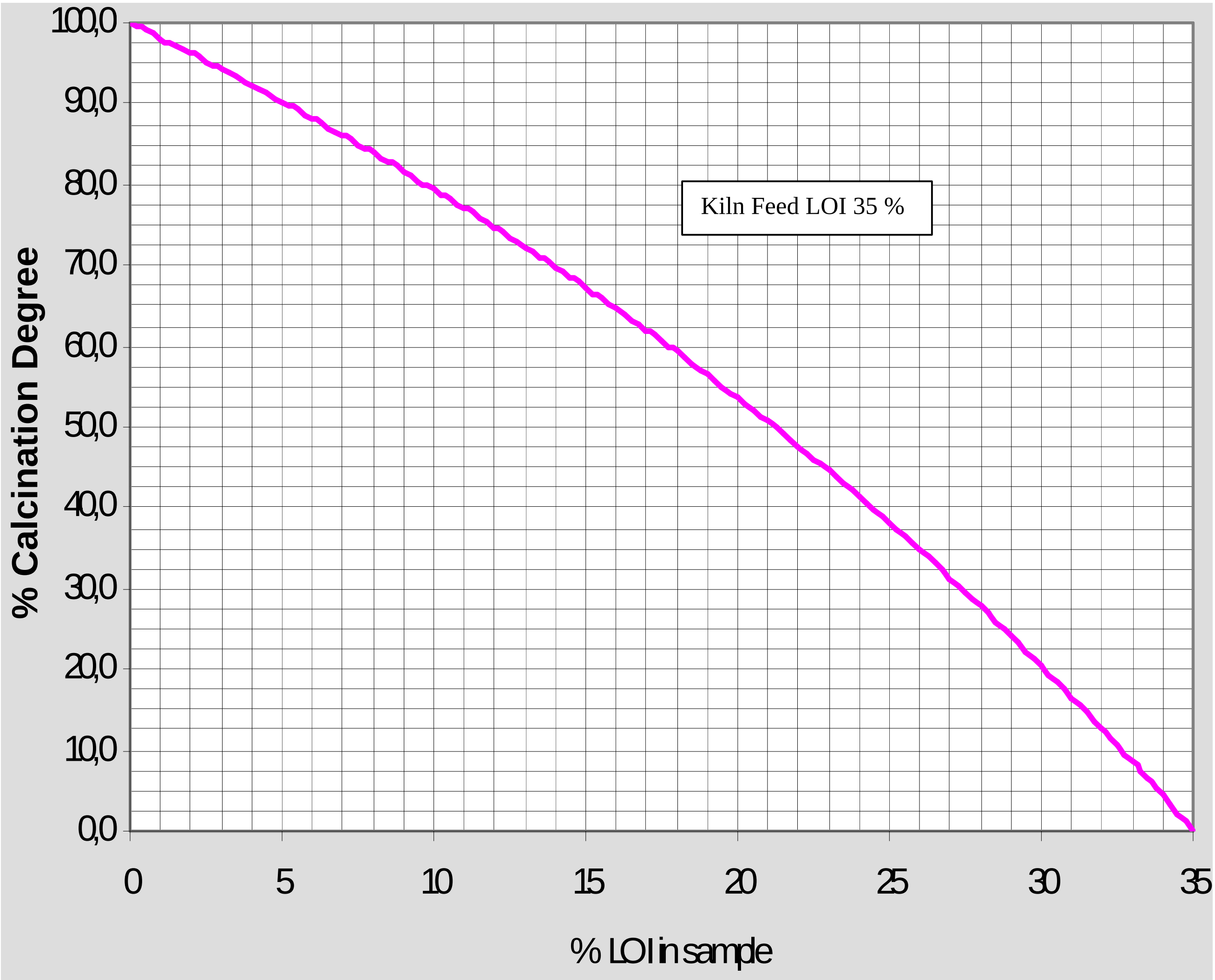
$$\mathbf{CaO}(1400°C)=0.33x(\mathbf{LSF})+2,5x(\mathbf{MS})+\mathbf{K_1}x\mathbf{Ac}(45\mu)+\mathbf{K_2}x\mathbf{R}(125\mu)+\mathbf{X}$$

Ac(45μ) is the acid (acetic) insoluble residue of 45 micron. **R**(125μ) is a total residue at 125 micron. $\mathbf{K_1}$ and $\mathbf{K_2}$ are constants between 0 and 1 determined by the specific mineralogy of the particular raw meal. The values represent the proportion and effect of oversized quartz and calcite in the respective residues on the free lime. **X** is a constant normally between -30 and -40.

The free lime estimations can also be used to compare the effect on burnability of changes in the characteristics of the raw meal with relation to the choice of a raw materials, the chemistry or the fineness.

Changes for improvement of Burnability (= Reduction of free CaO)				
	Proposed Change	**Resulting advantage**	**Potential problems**	**Comments Good ideas**
CHEMISTRY	**Reduce LSF**	▪ Slightly more liquid phase ▪ Less dust	▪ Less C_3S – lower potential strength	▪ Often easy to do, by adding less Limestone ▪ If LSF larger than app. 100, it may be impossible to burn to low free CaO. It is better to decrease LSF to achieve low CaO in clinker, as it is a waste to have excess calcite through the kiln being calcined heated and cooled. ▪ Microscopy of clinker can reveal if it is possible to burn the clinker to a lower free CaO. ▪ the primary reason for having too high LSF is incorrect Chemical Analyses of the raw mix. ▪ Unsatisfactory homogenisation of the raw materials will give fluctuations in LSF and affect the burnability in unforeseeable ways making it very difficult for the operator to operate the kiln.
	Reduce Ms	▪ More liquid ▪ Better granulometry - less dust ▪ Improved cooler efficiency	▪ Big clinker balls when too low Ms ▪ Slightly lower C_3S in clinker	▪ Should always be considered if dust is a problem ▪ Significant effect on burnability, but small effect on strength ▪ Ms > 2,5: consider a decrease ▪ Ms < 2,3: try to increase ▪ A decrease in Ms will often result in a decrease in quarts and silicates along with having a positive effect on the burnability.
	Reduce Ma	▪ Liquid starts at lower temperature ▪ Better granulometry	▪ Slightly lower C_3S	▪ Easy to do if iron ore is available ▪ Minor effect on burnability ▪ Longer time in kiln for good nodulisation
MINERALOGY	**Reduce coarse calcite particles**	▪ Easier for calcite particles to react	▪ Calcite is a soft material and will be affected by finer grinding ▪ Finer grinding will require more energy in the mill ▪ Possible mill capacity problems (lower production)	▪ Often the first and easiest choice, if the mill has extra capacity ▪ Relatively small effect on burnability ▪ Over-burning is often a problem because big free CaO particles from large Calcite particles are impossible to burn away. If the operator does not know this, the only option seems to be to burn harder – possibly resulting in dusty clinker ▪ No effect on cement quality ▪ Finer grinding will have minor effect on coarse silicates and quarts ▪ Will normally improve clinker grind ability
	Reduce coarse quarts particles	▪ easier to avoid big C_2S clusters ▪ Will normally improve clinker grind ability	▪ May require separate grinding of sand component i.e. more energy and investment	▪ Good effect on burnability ▪ Other components should be examined. Different sands may have identical chemistry but different sizes of quartz
WHAT ELSE	**Burn Harder** *OR* *add CaF_2* *OR* *Read about mineralised clinker*	▪ The production may be changed with acceptable free CaO	▪ Short brick life due to high temperature ▪ More NO_x emission ▪ More energy is needed	▪ If the free CaO can be kept at a reasonable value, the cement strength will be OK ▪ Harder burning will increase crystal sizes and result in clinker harder to grind resulting in more energy needed in the cement mill. ▪ The use of petcoke as fuel may be ruled out due to increased sulphur evaporation

Calcination Degree determined by Loss On Ignition (LOI)



The calcination degree is determined by LOI (loss on ignition) as an approximate value, as other materials other then CO_2 vanish during ignition. To reduce the influence of alkalis, sulphur etc. the LOI should be measured at 950 ^oC. The measured calcination degree of the hot meal from the lowest cyclone is influenced by the dust recirculation from the kiln. A high dust recirculation will result in a higher apparent degree of calcination.

$$\text{Calcination degree}(\%) = 100\left(1 - \frac{LOI_{sample}\left(100 - LOI_{kilnfeed}\right)}{LOI_{kilnfeed}\left(100 - LOI_{sample}\right)}\right)$$

Sampling of hot meal from the cyclone preheater.

To find the amount of residual hydrate water, unburned carbon, SO_3, alkali and choride in the cyclone material and in the hot meal entering the kiln, the sample has to be taken without being exposed to the air, and it has to be cooled fast. This avoids further evaporation of hydrate water and burning of carbon and pyrite.

For this purpose an FLS standard sampler has been made. A sketch of the sampler is shown on B7. The sampler has a cover which fits the cleaning holes in the cyclones, preventing air/oxygen from entering the cyclone during sampling. The sample cup is slim but has a relatively big stainless steel body, ensuring rapid cooling of the material.

Using the sampler.

Sampling is done in the following way:

1. Lower the cover so that it rests on the sampler cover

2. Open the cleaning hole and place the sampler cover over the cleaning hole, still keeping the cover and sampler cup together.

3. Lower the sampler cup into the material stream.

4. After 1 – 2 seconds draw the sampler up again to the cover.

5. Keep the sampler cup and cover together while removing it from the cleaning hole.

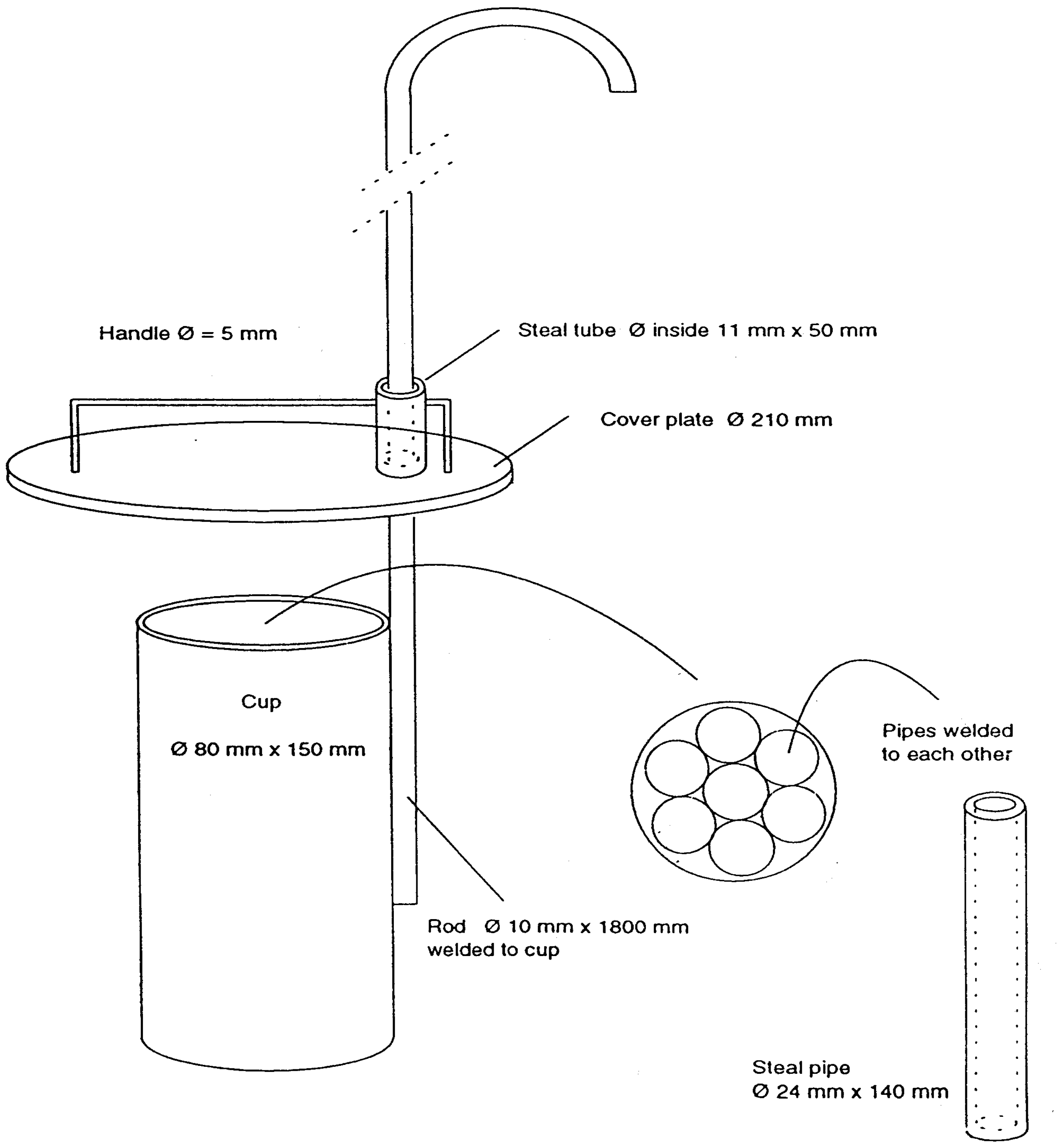
6. Close the cleaning hole

7. Place the sampler for a couple of minutes on the floor before removing the cover.

With this procedure the hot meal sample is cooled to less than 300 ^oC before being exposed to oxygen.

The samples should be kept in a closed and tight container to avoid absorption of humidity.

Fig. 1. Sampler cup and cover plate.



Proportioning- obtaining the required chemical composition

Today almost every proportioning system is automated. The control calculations are based on frequent analysis of raw meal (typically every hour), regular analysis of the raw materials and recorded consumptions of each raw material. Natural variations in the chemistry of the raw materials are common. The proportioning system must attempt to correct and compensate the proportions so that the average composition over a period (often 4 hours) converges with the target for the raw meal.

The numbers of parameters that can be controlled depend on the number of raw materials. With n different raw materials it is possible to control n-1 parameters. (i.e. With 3 raw materials 2 parameters can be controlled e.g. LSF and MS.)

Manual control of proportioning may be executed by an accounting balance of the parameters to be controlled. The difference between target and obtained value is calculated as the Δ parameter {ΔLSF=LSF (sample)-LSF (target)}. Other Δ parameter may be calculated and used in accounting balances, CaO, SiO2, MS, and C3S etc.

The accounting balance accumulates the contribution of (Δ*Production) from each sampling period. The duration of an accounting period is based on the ability of the homogenising system but often it is 4 hours. (Sample below based on LSF accounting)

Hourly Account	Target	Sample	Δ	P(t/h)	P*Δ	Σ(P*Δ)
1	95	92,4	-2,6	125	-325	-325,0
2	95	95,5	+0,5	134	+67	-258,0
3	95	95,8	+0,8	115	+92	-166,0
4	95	97,1	+2,1	124	+260,4	+94,4
5	95	94,2	-0,8	126	-100,8	-6,4

One strategy of corrective and compensating action would be to adjust the proportions to achieve a reduction of the accumulated error by 25-50% for the latest 4 hours of operation. The purpose being that the balance of the accumulated error must reach or cross zero within an accounting period.

Homogenisation of raw materials or meal

$$H = \sqrt{\frac{n}{2}};$$

(n: layer in the pile)

$$H = \frac{S_{IN}}{S_{OUT}};$$

To stabilise the chemical variations in a raw material, raw meal or a blended mixture of raw materials a storage facility with homogenising effect is used. The relation between the standard deviation of a chemical component entering and leaving the store is calculated as the homogenising factor (H). This factor rarely exceeds 10. Typically it is 2-6. Segregation can lower the efficiency of homogenisation.

To ensure a stable kiln product and operating conditions the raw meal must be homogenous with little variation of the chemical properties of the feed for the cement kiln. The homogenising factor of a store is determined by the relation between the standard variation of material entering and leaving the store. The lower the standard deviation of the store output to input the higher the homogenising factor.

Homogenisation test (24 hours)

24 hourly samples of input and output material are collected, 48 samples total. The time delay from sampling of input to output material shall correspond to the mean retention time of the material or until the quantity of material extracted from the silo corresponds to the content of the silo at the start of the testperiod. Each sample is prepared and analysed(X1, X2) 2 times, for either CaCO3, CaO, LSF or C3S. For each set of data - input and output the following calculations are made.

No	1st	2nd	Average	Diff. $(X1_i - X2_i)$	$(D_i)^2$	$(\bar{X} - X_i)^2$
1	$X1_1$	$X2_1$	X_1	D_1	$(D_1)^2$	$(\bar{X} - X_1)^2$
2	$X1_2$	$X2_2$	X_2	D_2	$(D_2)^2$	$(\bar{X} - X_2)^2$
3	$X1_3$	$X2_3$	X_3	D_3	$(D_3)^2$	$(\bar{X} - X_3)^2$
…	…	…	...	…	…	…
5(ex.)	23	33	28	10	100	$(\bar{X} - 28)^2$
…	…	…	…	…	…	…
24	$X1_{24}$	$X2_{24}$	X_{24}	D_{24}	$(D_{24})^2$	$(\bar{X} - X_{24})^2$
			$\bar{X}$		$\sum D_i^2 = (F)$	$\sum (\bar{X} - X_i)^2 = (W)$

$$X_i = \frac{(X1_i + X2_i)}{2}; \ \mathbf{i \in \{1..n\}}; \qquad \bar{\mathbf{X}} = \frac{\mathbf{1}}{\mathbf{24}} \sum_{\mathbf{n=1}}^{\mathbf{24}} \mathbf{X_i};$$

$$\mathbf{S_{Total}} = \sqrt{\frac{\mathbf{O}}{\mathbf{n-1}}} = \sqrt{\frac{\left(\sum X_i\right)^2 - n\sum X_i^2}{n(n-1)}} = \sqrt{VAR(X_{1..n})} = STDEV(X_{1..n})$$

$$\mathbf{S_{Analysis}} = \sqrt{\frac{\mathbf{F}}{\mathbf{2n}}} = \sqrt{\left(\frac{VAR(x1_i, x2_i,..) + VAR(x1_{i+1}, x2_{i+1},..) + ..}{n}\right)}$$

The standard deviation of a material is calculated as follows:

$$\mathbf{S_{Material}} = \sqrt{\mathbf{S^2_{Total}} - \frac{\mathbf{S^2_{Analysis}}}{\mathbf{q}}}$$

q represents the number of analysis made on a sample (normally 2). When it is not possible to prepare and analyse the samples 2 times (as when using the hourly routine analysis from log sheets) one or more similar samples can be prepared and analysed repeatedly to estimate the analytical standard deviation $S_{analysis}$. In case that homogenisation is calculated based on single analysis of the samples set q=1. Calculate the store homogenisation factor(H) as below:

$$\mathbf{H} = \frac{\mathbf{S_{Material}(input)}}{\mathbf{S_{Material}(output)}} = \sqrt{\frac{\mathbf{S^2_{Total}(input)} - \left(\mathbf{S^2_{Analysis}}\right)/\mathbf{q}}{\mathbf{S^2_{Total}(output)} - \left(\mathbf{S^2_{Analysis}}\right)/\mathbf{q}}}$$

If the deviation $S_{material}$(output) of the kiln feed from a homogenisation silo is less than one of the following values: 0,2 for %$CaCO_3$, 0,11 for %CaO, 1 for LSF or 3 for %C3S, then the kiln feed is considered homogenous. A calculation of the homogenisation factor will become meaningless when $S_{material}$(output) approaches 0 or becomes negative.

Sample raw materials

Sample compositions of some raw materials and cement clinker								
Raw materials	SiO2%	Al2O3%	Fe2O3%	CaO%	LOI%	LSF	SM	AM
High limestone	1,24	0,53	0,35	54,29	43,30	1255,3	1,41	1,51
Low limestone	9,97	1,71	1,15	46,70	37,80	152,2	3,49	1,49
Marl	27,20	5,36	4,32	35,40	22,70	41,5	2,81	1,24
Clay/Shale	77,90	8,32	5,48	1,88	3,68	0,8	5,64	1,52
Fly ash	51,00	27,70	11,70	1,16	0,37	0,6	1,29	2,37
Bauxite	18,20	45,70	9,80	0,01	25,60	0,0	0,33	4,66
Iron ore	5,84	1,43	87,16	1,14	1,00	1,5	0,07	0,02
Pyrite	12,20	2,58	68,70	2,55	8,74	3,1	0,17	0,04
Slag	35,20	13,11	0,48	40,80	2,00	35,7	2,59	27,31
Coal ash	49,80	29,30	7,52	3,65	0,98	2,0	1,35	3,90
Raw meal	14,10	3,76	2,25	43,30	34,90	95,4	2,35	1,67
Clinker	21,66	5,78	3,46	66,51	0,1	95,4	2,35	1,67

Volatiles – Circulation

The non combustible volatiles are components that melt and/or evaporate within the temperature range found in the kiln system. The significant volatiles are salts of alkalis ie. sulphates, chlorides and hydroxides. A cycle of volatiles that - evaporate in the hot part of the kiln - and condense in the cold part of the kiln and preheater, trap the volatiles in the kiln system and causes a continuous accumulation of the volatiles within the circulation loop.

Melting and boiling points of some volatile matter(°C)

Compound	Potasium (K)		Sodium (Na)	
	Melting pt.	Boiling pt.	Melting pt.	Boiling pt.
- oxide	-	350	-	1275
- carbonate	894	-	850	-
- sulphate	1074	1689	884	-
- chloride	768	1411	801	1440
- hydroxide	360	1320	328	1390

(Mixtures of the compounds may have lower melting points)

Limits of Volatile Components.

(The high limit only applies when the raw mix is easily burned and the alkali/sulphur ratio is favourable)

SP kiln system (without bypass)	Maximum allowable input of volatile components (LOI free raw meal basis)		
		NORMAL LIMIT	MAXIMUM LIMIT
	Chlorine as Cl	0,023 %	0,044 %
	Sulphur as SO_3	1,5 %	2,25 %

ILC calciner kiln system (without bypass)	Maximum allowable input of volatile components (LOI free raw meal basis)		
		NORMAL LIMIT	MAXIMUM LIMIT
	Chlorine as Cl	0,023 %	0,029 %
	Sulphur as SO_3	1,25 %	1,9 %

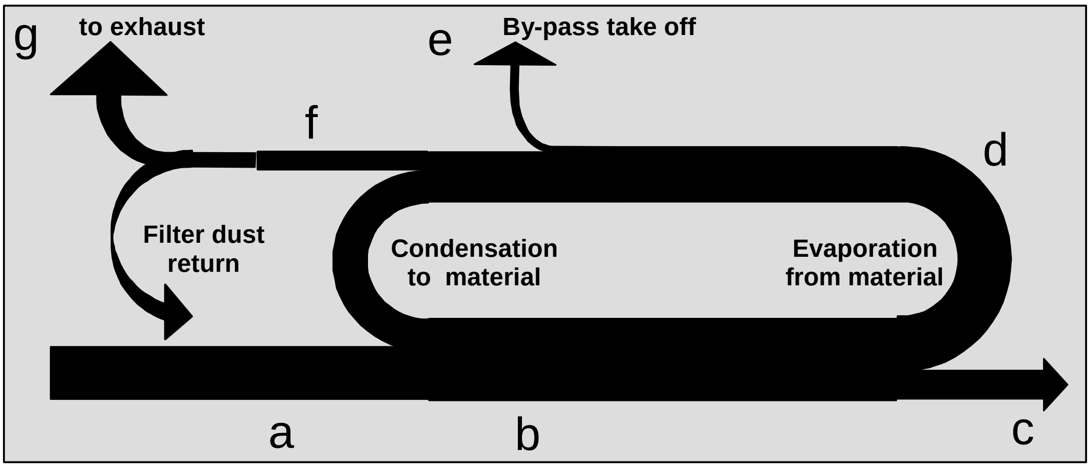
SP & ILC kiln system	Limits for volatile matter in bottom cyclone stage (LOI free hot meal basis)		
		NORMAL LIMIT	MAXIMUM LIMIT
	Chlorine as Cl	0,8 %	1,5 %
	Sulphur as SO_3	2,5 %	3,75 %

Content of Volatile Matter in Clinker

Limits for volatile matter in clinker to assure good quality		Limits for volatile matter in clinker when producing low alkali clinker	
Na_2O_{eq}	1,5 %	Na_2O_{eq}	0,6 %
SO_3	1,6 %	SO_3	1,6 %
Cl	0,1 %	Cl	0,1 %

(where $Na_2O_{eq} = Na_2O + 0,658 * K_2O$)

Circulation formulas:



Volatiles in:

a) Kiln feed including filter dust if returned.
b) Hot meal as sampled from the lower cyclone.
c) Clinker
d) Kiln gas (evaporated or on kiln dust).
e) By-pass dust
f) Dust lost from the preheater
g) Emission to the stack

Mass balance equations:
(1) **c+e+g=a;**
(2) **d=b-c;**
(3) **f=d-e;**
(4) **f+a=g+b**

$$Vol(LOI\ \ free) = \frac{Vol * 100}{(100 - LOI)}$$

Evaporation factor (ε): is the fraction of a volatile component that evaporates from the kiln burning zone instead of leaving the kiln with the clinker. ε = 1 means all volatile matter evaporates. ε = 0 means no evaporation - all volatile matter leave with the clinker.

Evaporation Factor (ε): $\varepsilon = \frac{d}{b} = \frac{b - c}{b}$

Circulation factor (K): is the relation of volatiles in kiln input (in hot meal) and the kiln feed.

Circulation factor (**K**): $K = \frac{b}{a}$

Valve (V): The relation of volatiles leaving the system at a certain point – (Stack or by-pass)

Valve (**V**): $V = \frac{g}{f}$

By-pass valve (**V$_b$**): $V_b = \frac{e}{d}$

Residual Component (R): The amount of volatile element leaving the system with the clinker.

Residual Component (**R**): $R = \frac{c}{a} = \frac{b - c}{a}$

Typical values for e and V.

		K_2O	Na_2O	Cl	SO_3
		(Cl-free)			
Evaporation factor	ε	0.10-0.40	0.10-0.25	0.990-0.996	0.30-0.90
Kiln (wet nodule-op.)	V_o	0.50	0.70	0.70	0.60
Kiln (wet dust op.)	V_o	0.40	0.60	0.60	0.40
Kiln (long dry)	V_o	0.20	0.50	0.60	0.40
Kiln (1 stage)	V_o	0.55	0.80	0.60	0.35
Kiln (2. stage)	V_o	0.70	0.85	0.80	0.60
Kiln (4 stage)	V_o	~1	~1	~1	~1
Kiln precalciner	V_o	~1	~1	~1	~1
Cycl. preheater, 1 stage	V_c	0.35	0.50	0.35	0.45
Cycl. preheater, 2 stages	V_c	0.20	0.45	0.20	0.30
Cycl. preheater, 4 stages	V_c	0.15	0.40	0.05	0.15-0.50
Dedusting cyclone valve	V_c	0.60	0.70	0.50	0.55
Raw mill valve	V_m	0.60	0.80	0.70	0.30
Cooling tower valve	V_{kt}	~1	~1	~1	~1
Elec.Static Precipitator	V_f	0.40	0.70	0.30	0.50-0.80

Sulphur / Alkali Ratio

The concentration of sulphur may increase to a point where it affects kiln operation causing build ups. Both overall quantity and relative proportions to the amount of alkali may be the cause. Sulphur, not combined with alkali, is more damaging to kiln operation than sulphate compounds such as K_2SO_4 and Na_2SO_4. In the right proportions alkali can combine with sulphur and become built-in in the clinker minerals resulting in low evaporation factors. Sulphur in excess will form the more volatile $CaSO_4$ which has a high evaporation factor.

Equation to estimate optimum ratio between sulphur and alkalis:

$$\left(\frac{\mathbf{SO_3}}{\mathbf{Alk}}\right)_{\text{optimum}} = \frac{\dfrac{\mathbf{SO_3}}{\mathbf{80}}}{\dfrac{\mathbf{K_2O}}{\mathbf{94}} + \mathbf{0{,}5} \times \dfrac{\mathbf{Na_2O}}{\mathbf{62}}} \approx \mathbf{1{,}1}$$

The sulphur and alkalis are the total input. If the ratio exceeds 1,1 it is held that an amount of sulphur is present in the kiln material which is not covered by alkalis, and “excess” sulphur will form $CaSO_4$.

Excess Sulphur (E.S.) is expressed in gram SO_3 per kg clinker:

Equation:

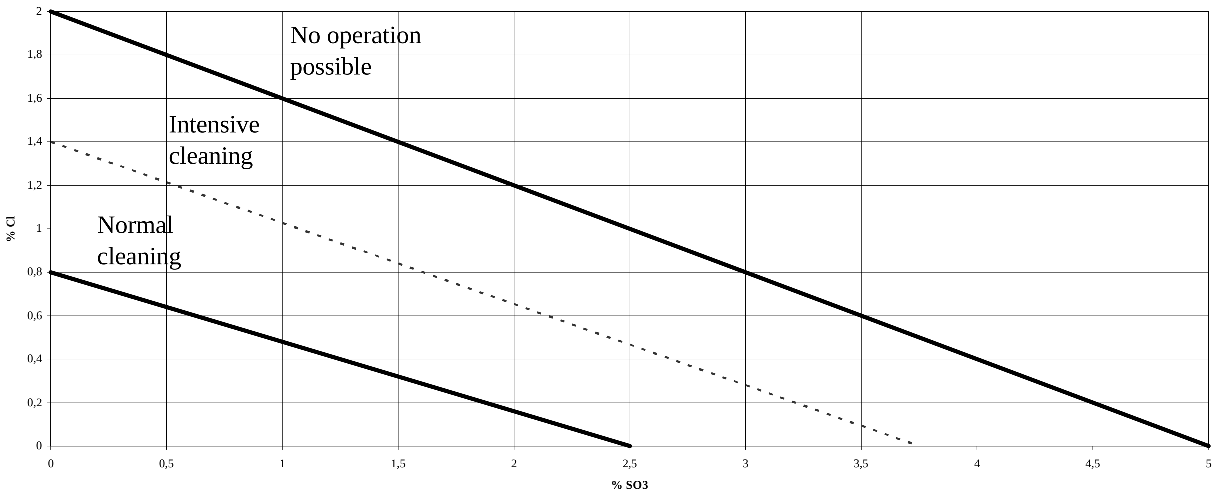
$$\mathbf{E.S. = 1000 \times SO_3 - 850 \times K_2O - 650 \times Na_2O \; [g\, SO_3 / 100\ kg\ cl]}$$

Limits:
The limit on excess sulphur is given to be in the range of 250 – 600 g/kg clinker.
The high limit is for easy burning material
The lower limit is for hard to burn material.

Inputs		Vm_i (%)	Na_2O	K_2O	S^*/SO_3	Cl	LOI	Clinker basis	Comment
Raw meal (kiln feed)			0,21	0,55	0,13	0,059	34,90	1,520 kg	Sulphur as SO3 in raw meal
		(LOI free)	**0,323**	**0,845**	**0,200**	**0,091**	-		**Vm_i x 100 / (100 - LOI)**
55% Coal (ash) (calorie basis)			1,00	0,50	2,00 *	0,25	-		Volatile except S on ash basis
		calc. to clinker	**0,008**	**0,004**	**0,322**	**0,002**	-	0,0077 kg	**Vm_i * 55% * 750 [kcal/kg cl] / 6400 [kcal/kg coal] * 12 [ash%] / 100**
45% oil/petcoke w. sulphur (calorie basis)					3,70 *				*Sulphur as S in fuel (SO3=S*80/32)
					0,359				**(*) $V_{SULPHUR}$ * 45% * 750 [kcal/kg cl] / 8700 [kcal/kg] * 80 / 32**
Input sum	a		**0,330**	**0,849**	**0,881**	**0,093**			
Output		Vm_i (%)	Na_2O	K_2O	SO_3	Cl	LOI	Clinker basis	
Clinker	c		**0,24**	**0,68**	**0,78**	**0,003**	-	1,000 kg	
By-pass dust			2,70	8,62	4,55	5,000	15,00		
	e	(LOI free)	**3,176**	**10,141**	**5,353**	**5,882**		0,009 kg	
Preheater dust			0,50	0,63	0,43	0,300	34,90		
	g	(LOI free)	**0,768**	**0,968**	**0,661**	**0,461**		0,080 kg	
Output sum			**0,330**	**0,849**	**0,881**	**0,093**			
Cyclone sample		Vm_i (%)	Na_2O	K_2O	SO_3	Cl	LOI		Comment
			0,76	1,20	0,82	0,530	15,00		
Hot meal	b	(LOI free)	**0,89**	**1,41**	**0,96**	**0,624**	-		**Vm_i x 100 / (100 - LOI)**
Circulation calculations		Vm_i (%)	Na_2O	K_2O	SO_3	Cl			
Evaporation factor		e	0,73	0,52	0,19	0,995			**e = (b-c) / b**
Cirkulation factor		**K**	2,71	1,66	1,10	6,74			**K = b / a**
By-pass valve		**V_b**	0,04	0,12	0,26	0,09			**V_b = e / (b-c)**
Valve		**V**	0,10	0,12	0,39	0,06			**V = g / f = g / (b-a+g)**
Residual component		**R**	0,73	0,80	0,89	0,03			**R = c / a**

Guidelines for critical concentration of Cl and SO3 in bottom stage Material

Bottom Stage Material
Guidelines for Critical concentrations for Cl and SO3 from wet lab



Thumb Rule

To avoid problems caused by SO_3 and Cl.

2 ´ Cl + SO_3 < 3,5

in bottom stage material

Properties of typical oils

		Gas-oil	Light Fuel oil	Heavy Fuel oil
Chemical composition				
C	%	86.3	86.2	86.1
H	%	12.8	12.4	11.8
S	%	0.9	1.4	2.1
Density at: 0 °C	kg/l	0.880	0.905	0.960
15 °C	kg/l	0.870	0.895	0.950
2 °E	kg/l	0.880	0.865	0.880
Temperature for 2 °E	°C	0	60	120
Specific heat	kcal/kg/°C	0.485	0.480	0.465
Calorific heat value				
Gross(H_{sup})	kcal/kg	10875	10550	10375
Net (H_{inf})	kcal/kg	10200	9900	9750
Combustion air	kg/kg	14.4	14.2	14.0
	Nm^3/kg	11.1	11.0	10.8
Combustion gases	Nm^3/kg	11.80	11.68	11.51
(wet, O_2 free)				
CO_2+SO_2	vol. %	13.7	13.9	14.1
N_2	vol. %	74.3	74.3	74.5
H_2O (g)	vol. %	12.0	11.8	11.4
Dew point	°C	50	50	49
Ignition temperature	°C	300 – 350		
Theoretical flame temperature	°C	2160	2120	2120

The heavy fuel oil used in cement plants is normally preheated to a viscosity of approx. 2 °Engler to ensure a good atomisation. This viscosity is normally reached at 120 - 150 °C.

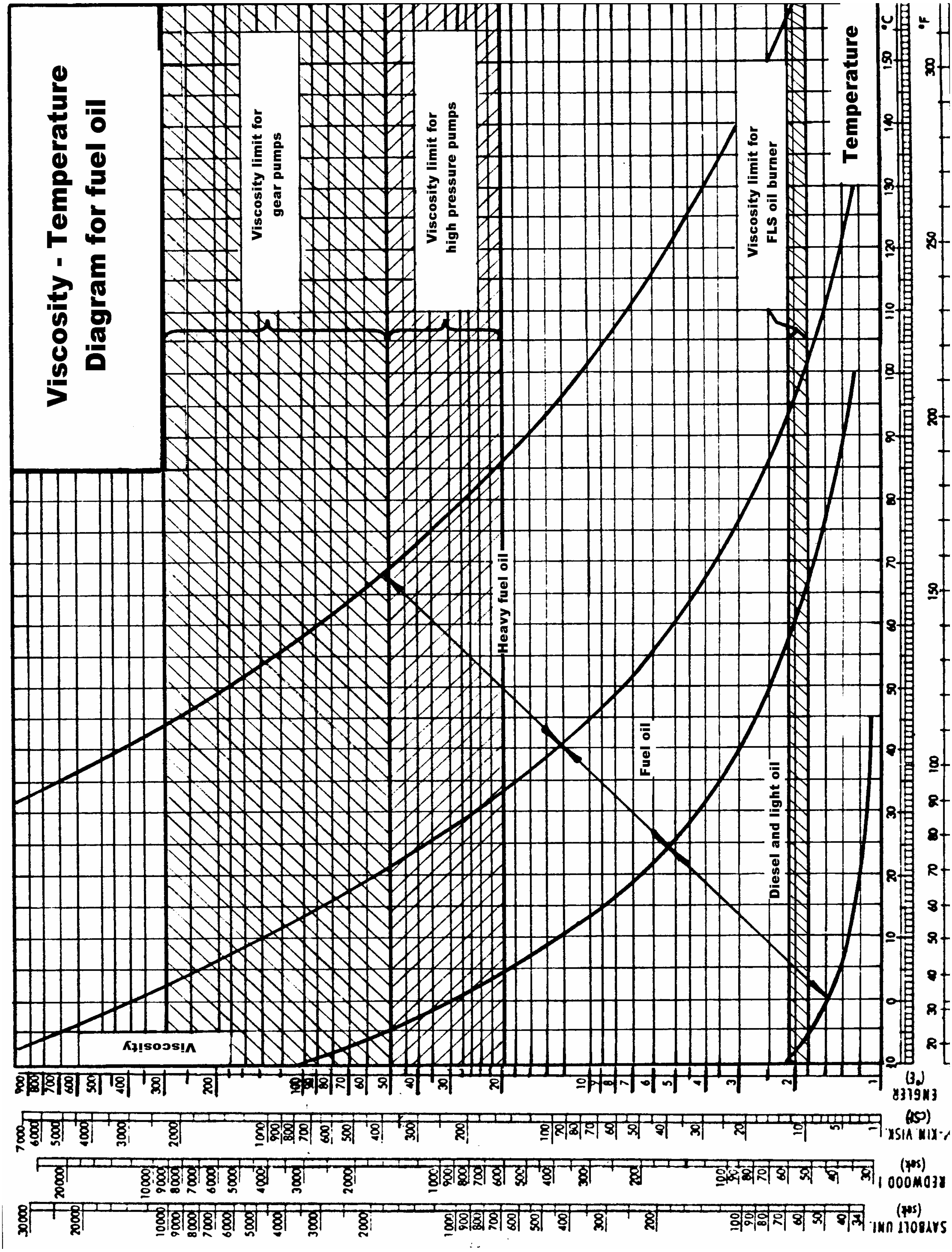
Calorific conversion

To obtain ?	**kcal/kg**	**MJ/kg**	**Btu/lb**
multiply ***kcal/kg*** by	1	4.187×10^{-3}	1.80
multiply ***MJ/kg*** by	238.8	1	429.9
multiply ***Btu/lb*** by	0.5556	2.326×10^{-3}	1

Oil viscosity conversion table

Centistoke	Engler Deg.	Redwood in secs.	Saybolt Universal Sec.	Saybolt Furol	Centistoke	Engler Deg.	Redwood in secs.	Saybolt Universal Sec.	Saybolt Furol
	1,0				87,5	11,5	351	408	44
	1,1				91,0	12,0	367	426	46
3,0	1,2	33,3			95,0	12,5	381	444	48
4,0	1,3	35,7	39,4		99,0	13,0	396	462	49
5,0	1,4	38,5	42,8		102,5	13,5	412	480	51
6,1	1,5	41,9	47,0		106,5	14,0	427	500	53
7,2	1,6	45,0	50,5		110,0	14,5	443	515	55
8,4	1,7	47,8	53,8		114,0	15,0	459	530	56
9,6	1,8	50,8	57,5		118,0	15,5	473	545	57
10,8	1,9	54,0	61,0		121,5	16,0	489	560	59
12,0	2,0	57,5	65,0	13	125,5	16,5	504	578	61
14,0	2,2	64,2	73,0	13	129,0	17,0	520	595	62
16,0	2,4	70,3	80,5	14	133,0	17,5	534	612	64
18,0	2,6	77,0	88,0	15	137,0	18,0	549	630	66
19,5	2,8	83,6	95,5	15	140,5	18,5	565	648	68
21,0	3,0	90,3	103	16	144,0	19,0	580	665	70
23,0	3,2	96,7	110	17	148,0	19,5	595	682	73
24,5	3,4	103	118	17	152,0	20,0	610	700	75
26,0	3,6	110	125	18	156,0	20,5	625	718	77
28,0	3,8	116	132	18	160,0	21,0	641	735	79
29,5	4,0	122	140	19	163,5	21,5	655	752	81
33,5	4,5	138	158	21	167,0	22,0	670	770	83
37,5	5,0	153	176	22	171,0	22,5	686	788	84
41,0	5,5	169	193	24	175,0	23,0	700	805	86
45,0	6,0	185	211	26	178,5	23,5	716	822	88
49,0	6,5	201	229	27	182,0	24,0	731	840	90
53,0	7,0	217	247	29	186,0	24,5	747	858	92
57,0	7,5	233	266	30	190,0	25,0	772	876	96
61,0	8,0	248	283	32	197,5	26,0	800	912	96
65,0	8,5	264	301	34	205,0	27,0	828	950	100
69,0	9,0	280	318	35	213,0	28,0	856	988	104
73,0	9,5	295	336	37	220,0	29,0	886	1026	108
76,0	10,0	305	354	39	228,0	30,0	915	1065	112
80,0	10,5	320	372	41	236,0	31,0	940	1100	115
83,5	11,0	336	390	42	243,0	32,0	965	1135	118

Viscosity Diagram



Properties of Typical Coals

		Lignite	Bituminous	Anthracite
Ranges of:				
Total Moisture	%	40 – 50	5 – 10	0 – 3
Hygroscopic moisture	%	10 – 25	1 – 3	1
Volatiles	%	40 – 50	10 – 40	5
Ash	%	5 – 25	10 – 20	5 – 10
		Commercial grade samples		
Chemical composition				
C	%	56	70	78
H	%	4	3	2
S	%	1	1	1
N + O	%	19	3	2
Calorific Heat Value				
Gross(H_{sup})	kcal/kg	5120	6625	7100
Net (H_{inf})	kcal/kg	4820	6310	6900
Combustion Air	kg/kg	7.1	9.2	9.9
	Nm^3/kg	5.5	7.1	7.6
Combustion gases	Nm^3/kg	6.0	7.4	7.8
(wet, O_2 free)				
CO_2 +SO_2	vol. %	17.8	17.6	18.9
N_2	vol. %	72.2	75.9	76.5
H_2O(g)	vol. %	10.0	6.5	4.5
Dew Point	°C	46	38	31
Ignition temperature	°C	450 – 600		
Smouldering temperature	°C	200 – 300		
Theoretical Flame temperature	°C	2150		

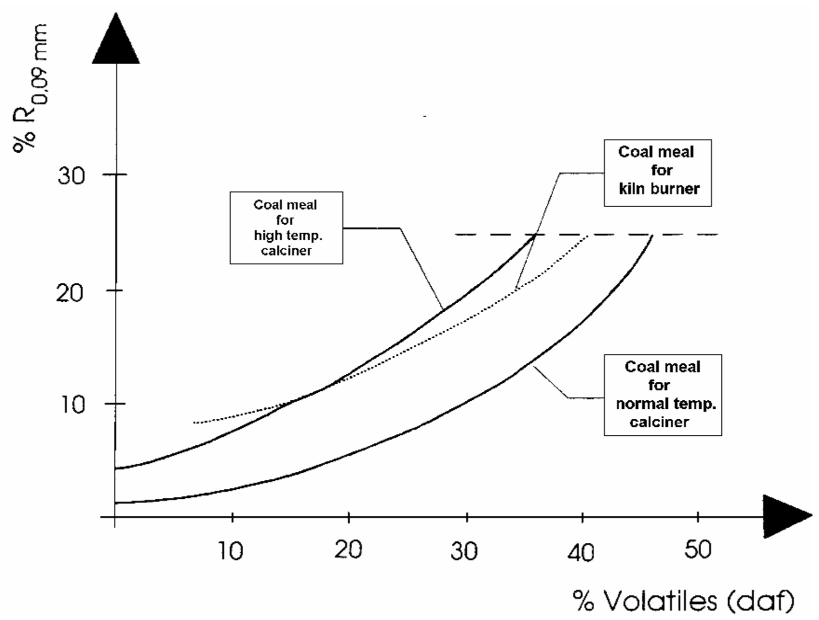
Calorific conversion

To obtain ?	**kcal/kg**	**MJ/kg**	**Btu/lb**
multiply ***kcal/kg*** by	1	4.187×10^{-3}	1.80
multiply ***MJ/kg*** by	238.8	1	429.9
multiply ***Btu/lb*** by	0.5556	2.326×10^{-3}	1

Coal combustion

The speed of combustion is increased with the reaction surface of the coal particles and the temperature. The surface is increased by grinding the coal to a higher fineness represented by a lower residue on a sieve (standard 90 micron). The combustion temperature is reduced by the presence of ash, dust or calcinating carbonate in the raw meal and excess air or gases not taking part in the combustion such as water vapour, CO_2 or nitrogen.

Recommended fineness of coal for kiln and calciner.



A typical Coal Ash Composition

Component	(% by weight)
SiO_2	20 – 60
Al_2O_3	10 – 35
Fe_2O_3	5 – 35
CaO	1 – 20
MgO	0.3 – 4
TiO_2	0.5 – 2.5
$Na_2O – K_2O$	1 – 4
SO_3	0.1 – 12

Typical contents in different coal types of Volatiles, Ash and Hygroscopic moisture

Coal Types	Volatiles %	Ash %	Hygroscopic Moisture %
Anthracite	< 8	3 - 5	< 2
Semi anthracite	5 – 15	3 – 5	2 - 6
Quarter rich	15 – 20	5 – 8	2 – 6
Bituminous	20 – 30	8 – 15	2 – 6
Rich	30 – 40	10 – 20	2 – 6
Lignite	40 –50	15 – 30	10 – 15
Petcoke	< 15	< 2	< 1

Rules of Thumb

Coal

- Due to risks of fire and explosions coal should generally not be ground finer in $R_{0,09}$ than half of the percentage of volatiles.

Petcoke

- Petcoke to be ground as fine as possible
- $R_{0,09}$: 5 – 7% for kiln burner and 3 – 5% for high temperature calciner
- Petcoke requires a high temperature calciner

Drying of coal

The moisture content of raw coal varies within wide limits. Before firing the coal it is ground and dried in consideration of safety and calorific value of the coal. Besides the free moisture which evaporates at ambient temperature, the coal contains hygroscopic or inherent moisture, which is the moisture evaporated by heating the coal from ambient air dried equilibrium (30^{o}C) to 105^{o}C.

The risk of fire and explosions can be limited considerably if the coal meal contains a certain amount of residual water. The recommended residual water content depends on the content of hygroscopic moisture in the raw coal. As a guideline it can be recommended to dry to 1-2 % above of the hygroscopic moisture. In case of very high hygroscopic moisture some of it can be dried off. The residual moisture for different coal types typically lies in the following ranges:

Anthracite and Petcoke:	0.5 – 1.0 %
Bituminous coals:	1.5 –2.5 %
Lignite:	8 – 12 %

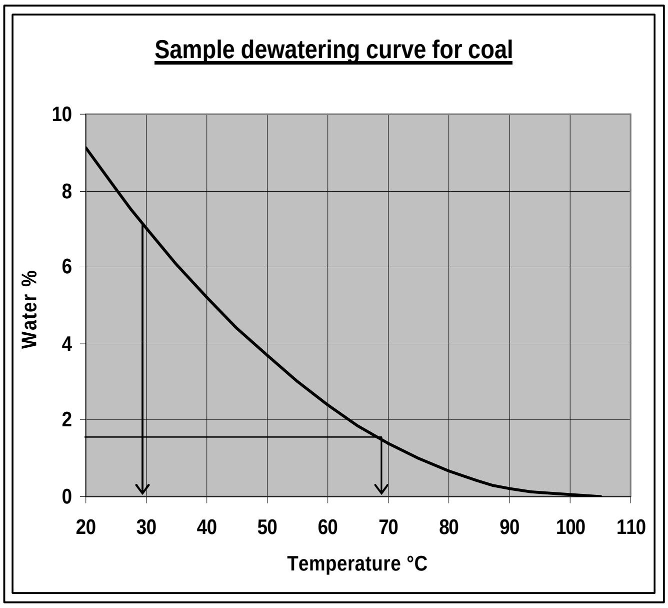
Dewatering curve

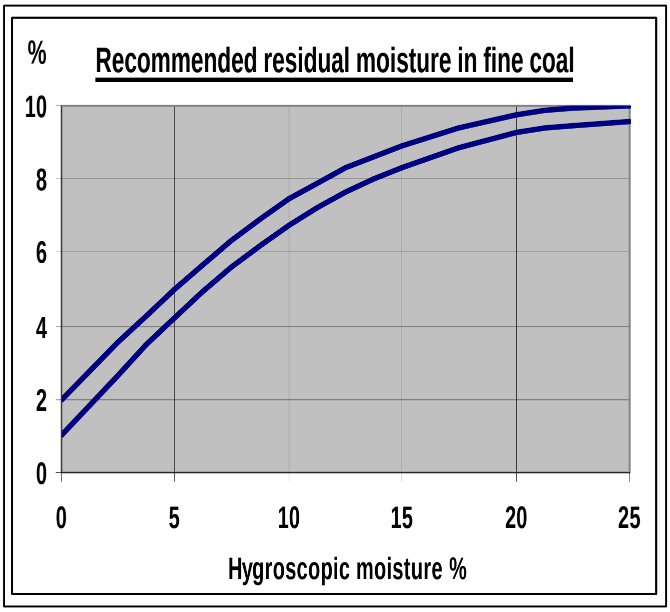
A dewatering curve shows residual water vs. temperature. In practice the mill outlet temperature needs to be slightly higher to obtain the desired residual moisture in the coal. The difference is due to the shorter retention time of the coal dust in the mill than in the laboratory oven. $(T_{Mill\ outlet} - T_{dewpoint} > 20\ ^oC)$

1. Crush a representative sample of raw coal to <5mm. Weigh out 500 grams of the sample and spread it in an open tray to a thickness of approx.1 cm.	Initial weight at t °C:	$W_{initial}$(g)
2. Dry the sample for 24 hours at 30^{o}C.	Weight after drying:	W_{30}(g)
3. Dry the sample for 5 hrs at 50^{o}C.	Weight after drying:	W_{50}(g)
4. Dry the sample a further 5 hours at 65^{o}C.	Weight after drying:	W_{65}(g)
5. Dry the sample a further 5 hours at 85^{o}C.	Weight after drying:	W_{85}(g)
6. Finally dry the sample for 2.5 hours at 105^{o}C.	Weight after drying:	W_{105}(g)

Calculate the moisture as percent of initial weight using formula below and plot moisture against temperature:

$$Moisture\ content(\%) = \frac{w_{initial} - w_{(t)}}{w_{initial}} \times 100\ (\%)$$





Coal analysis

Coal analysis

The **proximate** analysis of coal is the measurement of moisture, volatiles and ash. The remainder up to 100% is calculated as the fixed carbon. The **ultimate** analysis is the measurement of carbon, hydrogen, sulphur and nitrogen in the coal. The remainder up to 100% minus ash and moisture is calculated as the oxygen content. The **calorific heat** content is analysed in a 'bomb' calorimeter where a coal sample is burned in a closed vessel and the temperature increase of the isolated system is measured. Further analysis such as ash composition, specific heavy metals or trace compounds can be applied when required.

Analysis basis

The results of a solid fuel analysis can be presented on different basis.

- The [ar] basis (**a**s **r**eceived) is the sample itself as received at the laboratory without any drying treatment.
- The [ad] basis (**a**ir **d**ried) is the sample after drying at 30°C for 24 hours. The [ad] conditioned sample is also called **a**s **a**nalysed and is the basis for most analysis. Any free moisture has been evaporated. Residual moisture in the sample is called inherent or hygroscopic moisture.
- The [d] basis (dry) is the sample after drying at 105°C to constant weight.
- The [daf] basis (**d**ry and **a**sh **f**ree) is a calculated sample basis without any content of moisture and ash.
- The [dmmf] basis (**d**ry **m**ineral **m**atter **f**ree) is a calculated sample basis similar to [daf] without any content of moisture and mineral matter.

Base conversions

M_{Free}: Free moisture, surface moisture (on [ar] basis).
M_{ad}: Inherent moisture or hygoscopic moisture (on [ad] basis).
M_T: Total moisture (on [ar] basis)

$$M_T = M_{Free} + M_{[ad]} * \left(1 - \frac{M_{Free}}{100}\right)$$

To obtain → / multiply ↓	As Received[ar]	Air Dried[ad]	Dry basis[d]
[ar] by	-	$\frac{100 - M_{[ad]}}{100 - M_T}$	$\frac{100}{100 - M_T}$
[ad] by	$\frac{100 - M_T}{100 - M_{[ad]}}$	-	$\frac{100}{100 - M_{[ad]}}$
[d] by	$\frac{100 - M_T}{100}$	$\frac{100 - M_{[ad]}}{100}$	-

(to obtain **[daf]** multiply **[d]** by $100/(100 - Ash_{[d]})$)

Sample proximate analysis			[ar]	[ad]	[d]	[daf]
Free moisture	M_{Free}	%	3,60			
Inherent moisture	$M_{[ad]}$	%		4,40		
Total moisture	M_T	%	7,84			
Ash	**Ash**	%	13,50	14,00	14,65	
Volatiles	**Vol.**	%	32,50	33,71	35,27	41,32
Fixed carbon(calc.)	**FC**	%	46,16	47,88	50,09	58,68
Sulphur	**S**	%	2,30	2,39	2,50	2,92

Estimated calorific values from ultimate analysis (Dulong)

$$H_{Net} = 80{,}8 * C\% + 287 * \left(H\% - O\%/8\right) + 22{,}45 * S\% - 6{,}0 * H_2O\% \quad (kcal/kg)$$
$$H_{Gross} = 80{,}8 * C\% + 339{,}4 * H\% + 22{,}45 * S\% - 35{,}9 * O\% \quad (kcal/kg)$$

Conversion – Gross/Net Calorific Value
(ISO, for As Received figures)

$$\text{kcal/kg} : \mathrm{H_{Net}} = \mathrm{H_{Gross}} - 50{,}6 * \mathrm{H\%} - 5.85 * \mathrm{M\%} - 0{,}91 * \mathrm{O\%}$$
$$\text{MJ/kg} : \mathrm{H_{Net}} = \mathrm{H_{Gross}} - 0{,}212 * \mathrm{H\%} - 0.0245 * \mathrm{M\%} - 0.0008 * \mathrm{O\%}$$
$$\text{Btu/lb} : \mathrm{H_{Net}} = \mathrm{H_{Gross}} - 91.2 * \mathrm{H\%} - 10.5 * \mathrm{M\%} - 0.34 * \mathrm{O\%}$$

H% : hydrogen%; M% : moisture%; O% : oxygen %
(From ultimate analisis [ar])

For a typical bituminous coal with 10 % moisture and 25 % volatiles the difference between Gross and Net calorific values are approximately: 260 kcal/kg or 1.09 MJ/kg or 470 Btu/lb.

Properties of typical Natural Gases

		Dutch gas (Groningen)	Sahara	North Sea
Composition:				
CH_4	vol. %	81,76	86,50	91,80
C_2H_6	vol. %	2,73	9,42	3,50
C_3H_8	vol. %	0,38	2,63	0,80
C_4H_{10}	vol. %	0,13	1,06	0,30
$<C_5$	vol. %	0,16	0,09	0.33
Calorific heat value				
Gross(H_{sup})	kcal/Nm^3	8500	10780	9700
Net(H_{inf})	kcal/Nm^3	7580	9750	8760
Combustion Air:	kg/Nm^3	10,1	13,96	12,60
	Nm^3/Nm^3	8,44	10,80	9,75
Combustion gases	Nm^3/Nm^3	9,20	11,52	10,60
(wet, O_2 free)				
CO_2	vol. %	9,80	10,60	9,80
N_2	vol. %	71,60	71,70	71,70
H_2O(g)	vol. %	18,60	17,70	18,50
Dew point	°C	59		
Temperature drop from pressure reduction				
	°C/bar	0,3 – 0,5		
Ignition speed	m/s	18 – 28		
Ignition temperature	°C	600 – 700		
Theoretical Flame Temperature	°C	2050		

Calorific conversion

To obtain ?	**kcal/Nm^3**	**MJ/Nm^3**	**Btu/ Nft^3**
multiply ***kcal/Nm^3*** by	1	4.187×10^{-3}	0,112
multiply ***MJ/Nm^3*** by	238.8	1	26,75
multiply ***Btu/ Nft^3*** by	8,90	$37,39 \times 10^{-3}$	1

The ideal gas

The state of an ideal gas described with the following equation:

$$nR = \frac{p_0 * V_0}{T_0}\left(= \frac{p_1 * V_1}{T_1}\right) \quad thus \quad V_0 = V_1 * \frac{T_0}{T_1} * \frac{p_0}{p_1}$$

n:(No. of moles); *p*(pressure); *T*:temperature; *V*:Volume
R(Gas constant): 8,314 J/(°K*mol) or 1,987 cal/(deg*mol) or 8,205*10^{-2} (liter*atm)/(°K*mol)
[1 mole = 6,02205*10^{23} molecules]

Conversion formulas

To convert gas properties of atmospheric air or common exhaust gases from one state (set of temperature and pressure) to another state, the gas is commonly assumed to be ideal.

Density, ?(rho):(T:°C,p:mbar)

$$r(t,p) = r_0 * \frac{273{,}15}{273{,}15 + t} * \frac{1013 + p}{1013}\left[\frac{kg}{m^3}\right]$$

Flow, Q(T,p)

$$Q(t_2, p_2) = Q(t_1, p_1) * \frac{t_1}{t_2} * \frac{p_2}{p_1}\left[\frac{m^3}{h}\right]$$

Non-ideal gases

Significant deviation from ideal gas behaviour appears when the empty space between molecules is reduced as e.g. high pressures. Fuel gases deviate from the behaviour of an ideal gas. The correction factor Z is called the compressibility factor.

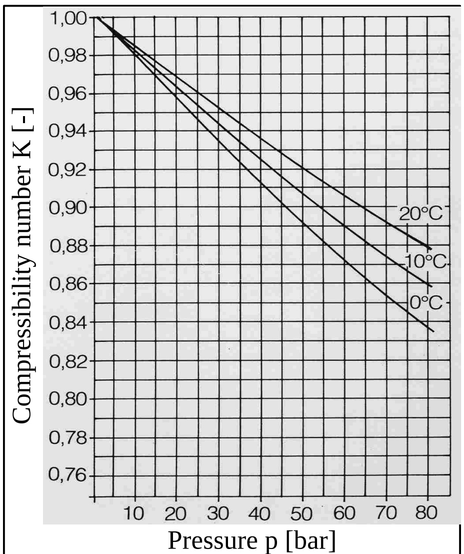
$$nRZ = \frac{p * V}{T}$$

Natural gas

To convert a natural fuel gas flow from m^3/h at a given temperature and pressure to Nm^3 (at 0°C):

$$Q_N = Q_{inst.} \times \frac{p + p_{amb}}{p_0} \times \frac{t_0 + 273{,}15}{t + 273{,}15} \times \frac{1}{k} \quad \left[Nm^3/h\right]$$

Q_N	(Nm^3/h)	Gas Volume flow (Norm Conditions)
$Q_{inst.}$	(m^3/h)	Gas Volume flow, uncorrected (as indicated)
p	(bar diff.)	Gas pressure (as indicated)
p_{amb}	(bar abs.)	Ambient pressure
p_0(=1)	(bar abs.)	Reference pressure (Norm Conditions)
t_0(=0)	(^{o}C)	Reference Temperature (Norm Conditions)
t	(^{o}C)	Gas temperature (as indicated)
Z	(-)	Compressibility factor (e.g. Natural gas at 5 bar Z=1,01)
K		Compressibility number (K=1/Z)



Compressibility number for natural gas (AGANX-19-mod)

Example of Gas Flow Calculation:

Data taken at local panel or gas station

$Q_{inst.}$	=	1976	(m^3/h)
p	=	5	(bar)
t	=	20	(^oC)

Ambient Conditions

p_{amb}	=	1,01325	(bar abs.)
t_{amb}	=	20	(^oC)

(Given in Flow meter calculation sheet. *From FLS*)

Normal Conditions:

p_0	=	1,01325	(bar abs.)
t_0	=	0	(^oC)

Compressibility Factor:

Z(=1/K) = 1.01 (-) .

$$Q_N = Q \times \frac{p + p_{amb}}{p_0} \times \frac{t_0 + 273{,}15}{t + 273{,}15} \times \frac{1}{k} \quad \left[Nm^3/h\right]$$

$$Q_N = 1976 \times \frac{5 + 1{,}01325}{1{,}01325} \times \frac{0 + 273{,}15}{20 + 273{,}15} \times 1{,}01 = 11036{,}01 \left[Nm^3/h\right]$$

Calculation of Gas consumption

A gas flow Q is often measured as the differential pressure across a duct section with reduced diameter or an orifice:

$$Q = k\sqrt{\frac{\Delta P}{r_t}}\ \left(\mathrm{m^3/min}\right)$$

Where:

k = flow coefficient with corresponding unit of flow (given by manufacturer)

ΔP = differential pressure across the orifice

$?_t$ = gas density at t (^{o}C) and ? P (mmWG)

$$Q_N = \frac{k \times 60}{r_0} \times \sqrt{\Delta P \times r_t} \quad \left(\mathrm{Nm^3/h}\right)$$

Where:

$$?_t = ?_0 \times \frac{273}{273 + t} \times \frac{B \pm Ps}{760} \quad \left(\mathrm{kg/m^3}\right)$$

Calculation of Lower Calorific Value H_i of a Gas from composition

H_i for various gases can be found in the table on page **E-13**

For the given gas mixture the lower heat value H_i can be calculated as the sum of the component heat values as below:

Analysis		Net heat values (H_i)		Unit
CH_4	91,1 %	8540	7779,9	kcal/Nm^3
C_2H_6	4,7 %	15300	719,1	kcal/Nm^3
C_3H_8	1,7 %	21800	370,6	kcal/Nm^3
C_xH_y	1,4 %	27400 (as C_4H_{10})	383,6	kcal/Nm^3
SUM			**9253,2**	kcal/Nm^3

Sample analysis:
Natural gas
CH_4....91,1%
C_2H_4....4,7%
C_3H_8....1,7%
C_xH_y....1,4%
N_2........0,6%
CO_2.....0,5%
O_2........0,0%

To calculate calorific heat to other conditions than 0°C and 760 mmHg

$$H_i\left(kcal/m^3\right) = H_i\left(kcal/Nm^3\right) \times \frac{273}{273+t} \times \frac{B+Ps}{760} \quad \left(kcal/m^3\right)$$

$$\left(\mathbf{t = 20^o\,C,\ B = 740\ mmHg,\ Ps = 700\,mmHg}\right)$$

$$H_i = 9253{,}2 \times \frac{273}{273+20} \times \frac{740+700}{760} = 16335{,}6\ \mathbf{kcal/m^3}$$

Thumb rule for gas
$H_S \sim 1{,}11 \times H_i$

Calorific Values H_s and H_i can sometimes be given in kcal/m^3 at 20 ^{o}C and 760 mmHg. To change to kcal/Nm^3 :

$$H_i\left(\mathrm{kcal/Nm^3}\right) = H_i\left(20°\mathrm{C}\right) \times \frac{273+20}{273} \quad \left(\mathrm{kcal/Nm^3}\right)$$

01.09.2003

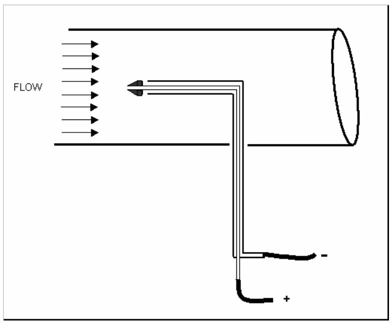
Gas Types	Molweight rounded	Specific volume Nm^3/kg	Specific weight kg/Nm^3	H_S H_{GROSS} $kcal/Nm^3$	H_I H_{NET} $kcal/Nm^3$	Ignition temperature °C	Comb.air
Hydrogen, H_2	2	11,117	0,09	3050	2570	530	2,38
Carbon Monoxide CO	28	0,800	1,250	3050	3050	610	2,38
Methane CH_4	16	1,397	0,715	9480	8540	645	9,52
Ethan, C_2H_6	30	0,745	1,342	16800	15300	530	16,70
Propane, C_3H_8	44	0,509	1,968	23700	21800	510	23,80
Butane , C_4H_{10}	58	0,386	2,594	29400	27400	490	30,90
Pentane , C_4H_{12}	72	0,311	3,219	37400	34600	480	38,10
Hexane , C_6H_{14}	85	0,260	3,844	44300	41000	590	45,40
Acetylene, C_2H_2	26	0,861	1,162	13800	13400	335	11,90
Ethylene, C_2H_4	28	0,799	1,252	14800	13900	540	14,30
Benzol, C_2H_6	78	0,287	3,484	34800	33500	710	36,70
Methanol , CH_3OH	32	0,699	1,430	7620	6180	500	7,15
Ethanol, C_2H_5OH	46	0,486	2,056	14500	13100	455	14,30
Acetone, CH_3COCH_3	58	0,385	2,592	19000	17650	500	19,00

Compositions and heat values of some alternative Fuels

(w/w)		Petcoke	Rubber	Wood	Rice Husk	Paper	Bone Meal
Carbon (C)	%	87,6	66,8	47,2	38,5	43,4	37,2
Hydrogen (H)	%	3,8	5,7	6,5	5,7	5,8	7,7
Sulphur (S)	%	5,1	1,2	0	0	0,2	0,5
Nitrogen (N)	%	1,5	0,4	0	0,5	0,3	5,8
Oxygen (O)	%	1,2	0,1	45,3	39,8	44,3	0,5
Moisture (H_2O)	%	0,6	0,8	0	0	0	18.9
Ash	%	0,2	25,0	1,0	15,5	6,0	29,4
Hs	Mj/kg kcal/kg	35,5 8440	30,9 7400	19,7 4700	14,8 3530	16,9 4040	
Hi	Mj/kg kcal/kg	34,5 8240	29,7 7090	18,3 4360	13,5 3230	15,6 3730	15,7 3750

Air Measurements with a Pitot –Tube

The measuring point in the duct must be on a straight stretch with a uniform flow, without obstructions like bends, dampers or flanges. There should be a straight stretch of minimum 5 x D before and 2 x D after the measuring position; where D equals the inside diameter. [For P_d measurements and Average calculation see page **F-2**].



Measuring Points		
Total Press	P_t	**+**
Static Press.	P_s	**-**
Dynamic Press.	P_d	**+ & -**

Where:

P_s =	Static Pressure	[mbar]	P_d =	Dynamic Pressure	[mbar]
B =	Barometric pressure	[mbar]	ρ_N =	Normal Density	[kg/m^3]
H =	Height above sea level	[m]	t =	Temp. of air/gas flow	[^{o}C]
Di =	Inside diameter of duct	[m]	v =	Velocity	[m/sec]
Q =	Air/gas Quantity	[kg/h] [m^3/h] or Nm^3/h]			

Barometric Press $$B = 1013 \times e^{-0{,}0001255 \times H} = (mbar)$$

Density $$\rho_t = \rho_N \times \frac{273}{273+t} \times \frac{B \pm P_s}{1013} = \left(kg/m^3\right)$$

Velocity

$$v = \sqrt{\frac{2g \times 10{,}2 \times Pd[mbar]}{\rho_t}} = \sqrt{\frac{19{,}6 \times 10{,}2 \times P_d(mbar)}{\rho_t}} = \sqrt{\frac{199{,}92 \times P_d[mbar]}{\rho_t}} = [m/sec]$$

Quantity $$Q = 3600 \times \frac{\pi}{4} \times D_i^2 \times v \times \rho_t = [kg/h]$$

$$Q = 3600 \times \frac{\pi}{4} \times D_i^2 \times v = \left[m^3/h\right]$$

$$Q_N = 3600 \times \frac{\pi}{4} \times D_i^2 \times v \times \frac{\rho_o}{\rho_t} = \left[Nm^3/h\right]$$

Air/gas Measurement with Double Pitot Tube – S Tube-

The double pitot tube or as often called S-tube is used to measure air flows in ducts with a high dust concentration.

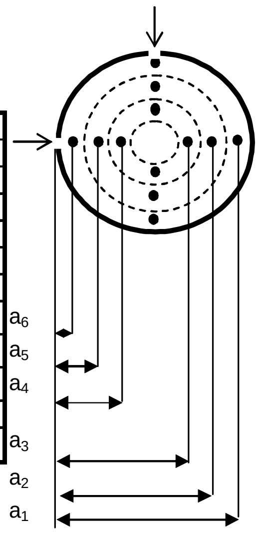
The dynamic pressure is corrected with the factor 0,86 before the normal formulas are used

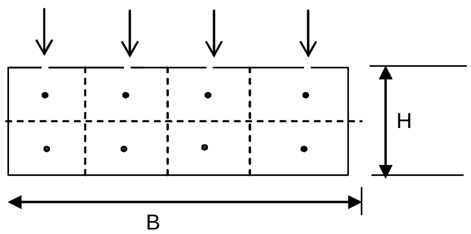
Measurement of Dynamik Pressure

The gas flow is never uniform throughout its cross section, and the Pd should be calculated as follows:-

$$Pd = \left(\frac{\sqrt{pd_1} + \sqrt{pd_2} + \ldots\ldots \sqrt{pd_n}}{n_{pd}} \right)^2$$

Diameter	0 > D ≥ 300	300 > D ≥ 700	700 > D ≥ 1500	1500 > D ≥ 2400	2400 > D ≥ 3400
	2 x 2	2 x 4	2 x 6	2 x 8	2 x 10
A1 =	0,85 * D	0,93 * D	0,96 *D	0,97 * D	0,97 * D
A2 =	0,15 * D	0,75 * D	0,85 *D	0,90 * D	0,92 * D
A3 =		0,25 * D	0,70 *D	0,81 * D	0,85 * D
A4 =		0,07 * D	0,30 * D	0,68 * D	0,77 * D
A5 =			0,15 * D	0,32 * D	0,66 * D
A6 =			0,04 * D	0,19 * D	0,34 * D
A7 =				0,10 * D	0,23 * D
A8 =				0,03 * D	0,15 * D
A9 =					0,08 * D
A10 =					0,03 * D

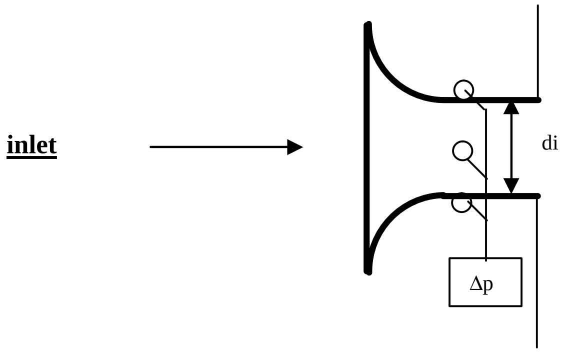




For a rectangel cross section a fictive diameter of D = 0,5 * (H + B) is Calculated, after which use the number of tabulated points

Example A flue duct measures inside 500 * 800 mm
(H = 500, B = 800)
D = 0,5 * (500 + 800) = 650
Corresponds to Table **(** 300 > D ≤ 700**)**
2 * 4 = 8 measuring points
Distributed as shown

Piezometer Air Flow Measurements



k factor for friction

FLS	Oelde	Solyvent
0,63	0,92-0,95	0,92-0,95

Calculation of cooler inlet air flow

The general formular for flow is:

$$\mathbf{Q} = \frac{\pi\, \mathbf{d_i}^2}{\mathbf{4}} \times \sqrt{\frac{\mathbf{2} \times \Delta \mathbf{p}}{\rho}} \; \left(\mathbf{m^3/sec}\right)$$

Where:

Q_{pd}	=	Fan design	[m^3/sec]
Q	=	Air Volume	[m^3/sec]
Q_N	=	Air Volume	[Nm^3/min]
ρ_N	=	Density	[1,293 kg/m^3]
ρ_t	=	Density	[kg/m^3]
Fan	=	Ventilator Type	[FLS, Solyvent, V. Oelden etc]
d_i	=	Inlet inside diameter	[meters]
Δp	=	Differential pressure	[Pascal]
k	=	Flow constant	[se table above]

If m^3/min and mbar are used for flow and pressure respectively:

$$\mathbf{Q} = \mathbf{60} \times \frac{\pi\, \mathbf{d_i}^2}{\mathbf{4}} \times \mathbf{k} \times \sqrt{\frac{\mathbf{2} \times \Delta \mathbf{p} \times \mathbf{100}}{\rho}}$$

If the flow is calculated in Nm^3/min, Q_N:

$$\mathbf{Qn} = \frac{\rho}{\rho_{\mathbf{N}}} \times \mathbf{60} \times \frac{\pi\, \mathbf{d_i}^2}{\mathbf{4}} \times \mathbf{k} \times \sqrt{\frac{\mathbf{2} \times \Delta \mathbf{p} \times \mathbf{100}}{\rho}}$$

or:

$$\mathbf{Qn} = \frac{\mathbf{60}}{\rho_{\mathbf{N}}} \times \frac{\pi\, \mathbf{d_i}^2}{\mathbf{4}} \times \mathbf{k} \times \sqrt{\mathbf{2} \times \Delta \mathbf{p} \times \mathbf{100} \times \rho}$$

Calculation of measuring range for piezometer

Calculation:

$$Q_N = Q ´ \frac{r}{r_N} = \qquad Nm^3/\text{min}$$

The maximum Air flow volume is given in the (PD diagram)
Increase this value by 10% and round to nearest 50.

$$Q_N = 1{,}1 ´ Q_{pd} \qquad Nm^3/\text{min}$$

<u>Calculation of transmitter Range</u>

$$Q_N = \frac{p}{4} ´ d_i^2 ´ \sqrt{\frac{2 ´ p}{r}} ´ \frac{r}{r_N} ´ 60 ´ k \qquad Nm^3/\text{min}$$

$$Q_N^2 = \frac{p^2}{16} ´ d_i^4 ´ 2 ´ p ´ \frac{r}{r_N^2} ´ 60^2 ´ k^2 \qquad Nm^3/\text{min}$$

$$p = \frac{Q_N^2}{d_i^4 ´ r} ´ \frac{16 ´ r_N^2}{p^2 ´ 2 ´ 60^2 ´ k^2} = \frac{Q_N^2}{d_i^4 ´ r} ´ \frac{16 ´ 1{,}293^2}{p^2 ´ 2 ´ 60^2 ´ k^2} \qquad (\text{Pascal})$$

Transmitter Range = 0 - p (Pascal) or 0 – p/100 (mbar)

Example:

Fan design	Q	=	**9,57**	[m^3/sec]
Air Volume	Q	=	**574,2**	[m^3/min]
Air Volume	Q_N	=	(calc)	[Nm^3/min]
Density	ρ_N	=	**1,293**	[kg/m^3]
	ρ_t	=	**1,06**	[kg/m^3]
Ventilator Type		=	**FLS**	[e.g. FLS, Solyvent, Oelde]
Inlet inside diameter	d_i	=	**0,71**	[meters]
Differential pressure	p	=	(calc)	[Pascal]
Friction constant	k	=	**0,63**	[see table page F3]

$$\mathbf{Q_N = Q \times \frac{\rho_t}{\rho_N} = \quad Nm^3/min}$$

$$\mathbf{Q_N = 574{,}2 \times \frac{1{,}06}{1{,}293} = \quad 471{,}8 \quad Nm^3/min}$$

Value to be increased by 10 %

$$\mathbf{Q_N = 1{,}1 \times 471{,}7 = 519 \quad Nm^3/min}$$

Rounded to the nearest 50 becomes **550 Nm³/min**

Measuring range: **0 - 550 Nm^3/min**

Transmitter range

$$\mathbf{p = \frac{Q_N^{\,2}}{d_i^{\,4} \times \rho} \times \frac{16 \times \rho_N^{\,2}}{\pi^2 \times 2 \times 60^2 \times k^2} = \frac{550^2}{0{,}71^4 \times 1{,}06} \times \frac{16 \times 1{,}293^2}{\pi^2 \times 2 \times 60^2 \times 0{,}63^2} \qquad (Pascal)}$$

p = 1065 Pascal = 10,65 mbar

Range 0 – 550 Nm^3/min ~ 0 - 10,65 mbar.

(NB measuring the pressure be sure that all the connections are tight and preferably use an inclined manometer)

Calculation Example of Flow range indication in CCR

Fan design	Q	=	**9,57**	[m^3/sec]
Air Volume	Q	=	**574,2**	[m^3/min]
Air Volume	Q_N	=	(calc)	[Nm^3/min]
Density	ρ_N	=	**1,293**	[kg/m^3]
	ρ_t	=	**1,06**	[kg/m^3]
Ventilator Type		=	**FLS**	[e.g. FLS, Solyvent, Oelde]
Inlet inside diameter	d_i	=	**0,71**	[meters]
Friction constant	k	=	**0,63**	[see table page F3]

Differential Transmitters Range Δp = 0 - 1000 [Pascal]

Note: Adjust / Check That :

- Square root must be activated
- Pressure indicating p_o is 0 Pascal , = mbar etc.
- If display is in %, indication must be 0 %
- If transmitter has no display you you measure 4mA when p_0 =0

Flow Range Calculation for CCR.

$$Q_{max} = \frac{\pi}{4} \times d_i^2 \times \sqrt{\frac{2 \times \Delta p_{max}}{\rho}} \times \frac{\rho}{\rho_N} \times 60 \times k \qquad Nm^3/min$$

$$Q_{max} = \frac{\pi}{4} \times 0.71^2 \times \sqrt{\frac{2 \times 1000}{1,060}} \times \frac{1.060}{1.293} \times 60 \times 0.63 = 532,9 \qquad Nm^3/min$$

$$Q_{max} = 533 \ Nm^3/min \quad \approx \underline{20\ mA}$$

$$Q_{min} = \frac{\pi}{4} \times d_i^2 \times \sqrt{\frac{2 \times \Delta p_{min}}{\rho}} \times \frac{\rho}{\rho_N} \times 60 \times k \qquad Nm^3/min$$

$$Q_{max} = \frac{\pi}{4} \times 0.71^2 \times \sqrt{\frac{2 \times 0}{1,060}} \times \frac{1.060}{1.293} \times 60 \times 0.63 = 0 \qquad Nm^3/min$$

$$Q_{max} = 0 \ Nm^3/min \quad \approx \underline{4\ mA}$$

<u>The scaling in the CCR should be 0 – 533 Nm^3/min</u>

Fan Curves:

In order to create a fan kurve at any given condition a base curve is needed.

	Base curve	Measured Values
Specific Weight	ρ_o	ρ
Fan Speed	n_o	n
Impeller Diameter	D_o	D
Power$_{shaft}$	kW_o	kW
Total pressure (Pt = Ps + Pd)	Pt_o	Pt
Gas Volume	Q	Q

The following relationships between the properties exists:

$$\mathbf{kW} = \mathbf{kW_o} \times \left(\frac{\mathbf{n}}{\mathbf{n_o}}\right)^3 \times \left(\frac{\mathbf{D}}{\mathbf{D_o}}\right)^3 \times \left(\frac{\rho}{\rho_o}\right)$$

$$Q = Q_o \times \left(\frac{n}{n_o}\right) \times \left(\frac{D}{D_o}\right)^3 \qquad Pt = Pt_o \times \left(\frac{n}{n_o}\right)^2 \times \left(\frac{D}{D_o}\right)^2 \times \left(\frac{\rho}{\rho_o}\right)$$

Pt is the pressure drop across the fan

For a fan working in a given changeable duct system the following applies:

- Air volume changes proportionally to the rpm.
- Pressure changes proportionally to rpm in second power
- Power changes proportionally to rpm in third power

If there is no fan curve, the power consumption at the shaft can be estimated according to the following equation:

$$\mathbf{kW} = \frac{\mathbf{Q} \times \Delta\mathbf{P}}{\mathbf{6114} \times \eta}$$

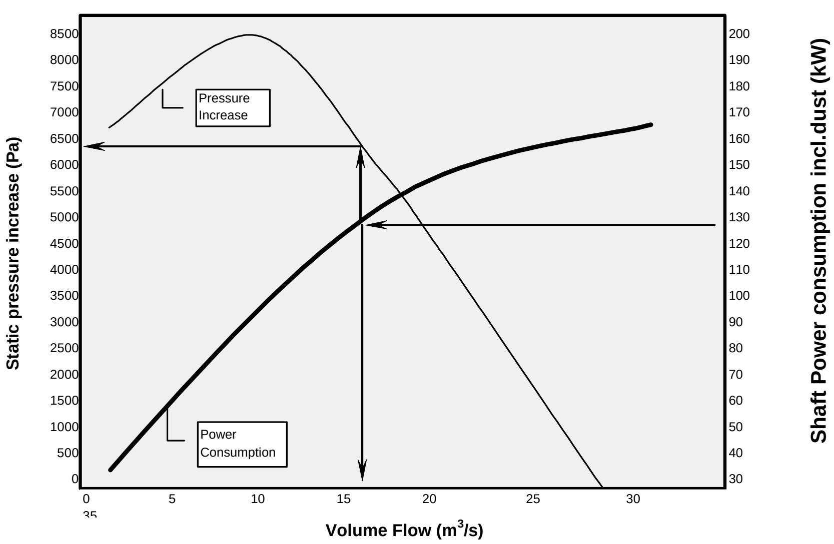
where:

η = fan efficiency for open impeller ~ 0,5 – 0,6

η = fan efficiency for closed impeller ~ 0,7 – 0,8

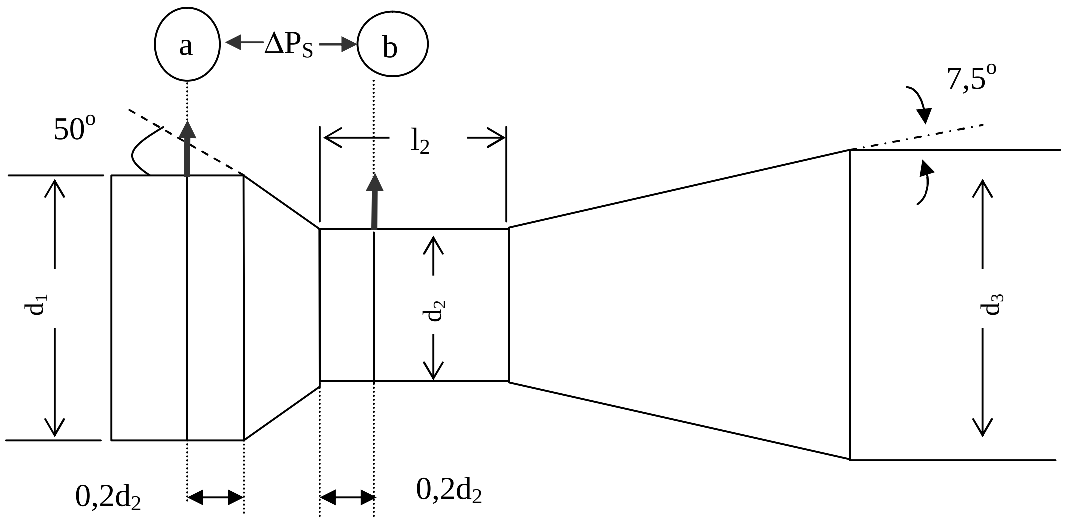
Q = gas volume (m^3/min)

ΔP = total pressure,(Pt = Ps + Pd), *inlet* + *outlet* (mmWG)



Flow Measurements with Venturi

Venturi with fixed dimension ratios



$d_1 = d_3$ (m) , $d_2 = 0{,}85 \times d_3$ (m) , $l_2 = 0{,}5 \times d_2$ (m),

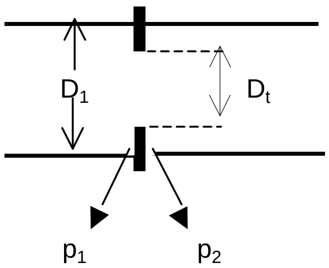
ΔP_s = Differential press. measured in mbar

K = (resistance coefficient of stretch a – b)
K is a given by the venture manufacturer or in some cases stamped on the venture.

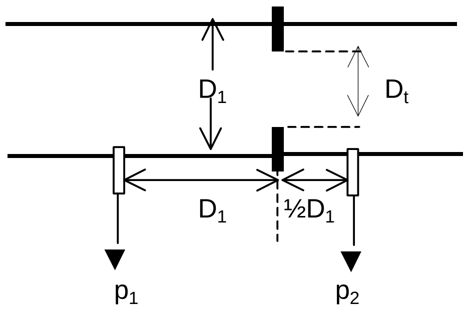
$$\mathbf{Q} = \frac{\mathbf{d_1^2} \times \pi}{\mathbf{4}} \times \sqrt{\frac{\Delta \mathbf{P_s} \times \mathbf{100}}{\rho} \times \frac{\mathbf{2}}{\left(\frac{\mathbf{1+K}}{\mathbf{0{,}522}} - \mathbf{1}\right)}} \qquad \left[\frac{\mathbf{m^3}}{\mathbf{s}}\right]$$

Approximate Flow calculation with concentric sharp edged orifice

Orifice with Corner Tapping



Orifice with D_1 and ½D_1 Tapping



Orifice Ratio D_t/D_1	β	0,2	0,3	0,4	0,5	0,6	0,7
Flow Coefficient	k	0,599	0,602	0,610	0,622	0,647	0,691
Estimated Orifice Head loss	%	92	88	82	74	65	52

(Assumed Reynolds number (Re) $10^5 < Re < 10^7$**)**

Data.

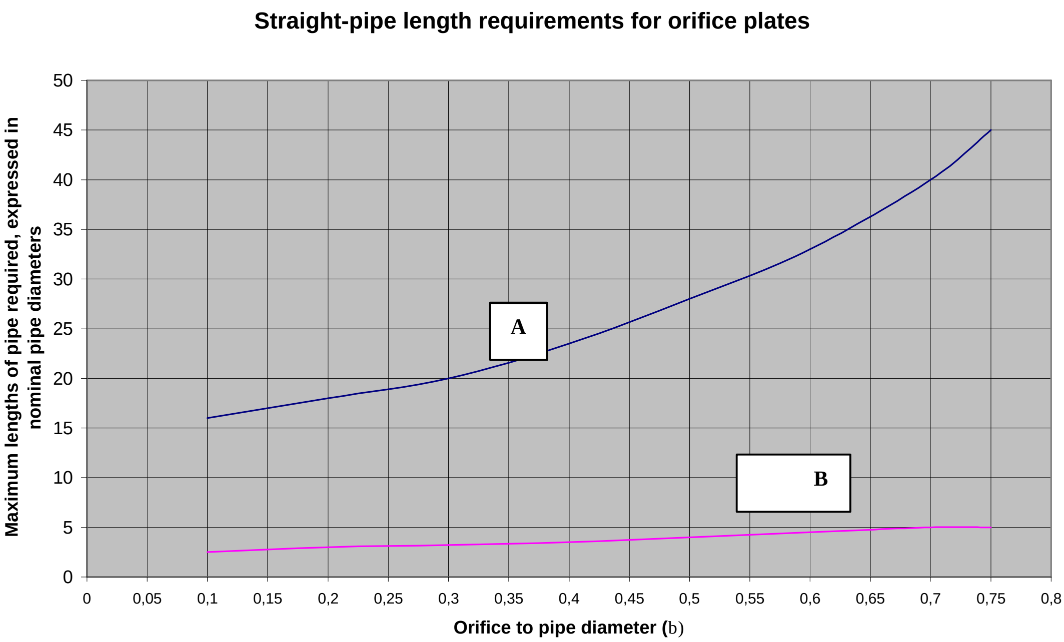
D_1 = Pipe diameter [m] D_t = Orifice diameter [m]
p_1 = Pressure before Orifice [Pascal] Unit = bar $*10^5$ [Pascal]
p = Pressure after Orifice [Pascal] A = Pipe Area [m^2]
ρ_t = Density [kg/m^3] ρ_N = Density 1,293 [kg/m^3]
A_t = Orifice Area [m^2]
k = Flow Coefficient [Find in table according to Orifice ratio β] *If b is between given numbers in table then interpolate.*

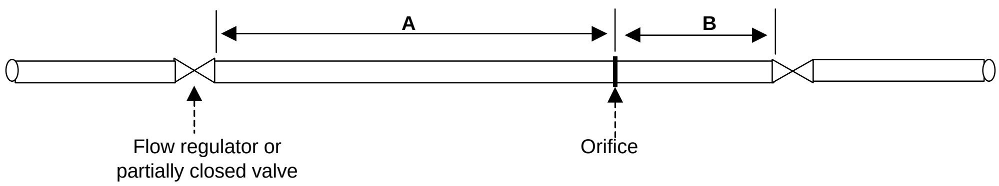
$$\mathbf{m} = \mathbf{k} \times \mathbf{A_t} \times \sqrt{\mathbf{2} \times \rho_t \times (\mathbf{p_1} - \mathbf{p_2})} \quad \mathbf{kg/sec}$$

$$\mathbf{Q} = \frac{\mathbf{m} \times \mathbf{3600}}{\rho_t} \quad \mathbf{m^3/h} \qquad \mathbf{Q_N} = \mathbf{Q} \times \frac{\rho_t}{\rho_N} \quad \mathbf{Nm^3/h} \qquad \mathbf{V} = \frac{\mathbf{Q}}{\mathbf{A}} \quad \mathbf{m/sec}$$

$$\rho_t = \rho_N \times \frac{\mathbf{273}}{\mathbf{273 + t}} \times \frac{\mathbf{B \pm P_s}}{\mathbf{101300(Pascal)}} \quad \mathbf{kg/m^3}$$

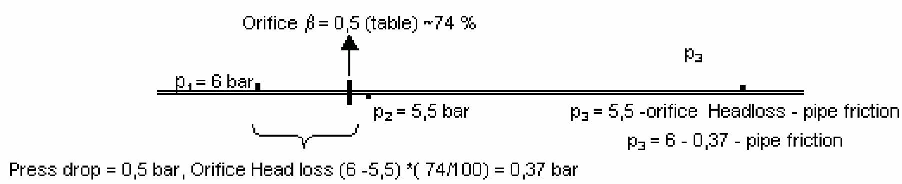
Required Position of an Orifice





Orifice Headloss

The % head loss indicated in the table informs what % of the measured pressure loss across the orifice will be permanent in the pipe after the pipe.



Minimum Combustion Air and L_{min}

The **Minimum Combustion Air** is the dry atmospheric air required to complete the combustion of a given fuel. It is also called the **Theoretical** or **Stoichiometric** air requirement. In calculations $\mathbf{L_{min}}$ represents the minimum combustion air.

- $\mathbf{L_{min,Flow}}$: When the minimum combustion air is used as basis for primary air or kiln air calculations it is expressed as an air flow. (Common units: [kg Air/h], [Nm3 Air/min])

- $\mathbf{L_{min,Heat}}$: The minimum combustion air is also expressed as a fuel dependent ratio of air to heat input. (Common units [kg Air/1000 kcal], [Nm^3 Air/MJ])

- $\mathbf{L_{min,Fuel}}$: In relation to a given fuel the minimum combustion air is expressed as a ratio of air to fuel. (Common units: [kg Air/kg Fuel], [Nm^3 Air/Nm^3 Gas])

Calculating the Minimum Combustion Air Flow ($L_{min,flow}$) from Production and Heat input or fuel consumption.

$$L_{min,\ Flow}\,[kg/h] = \frac{L_{min,\ Heat} * X * P}{24}$$

$$L_{min,Flow}[kg\ air/h] = L_{min,Heat} * F_{fuel} * H_{i,\ fuel}$$

P = Production ....tpd; **H_i** = Lower heat value of the fuel .... kcal/kg
F_{Fuel} = Fuel flow ....tph; **X** = Heat consumption .... kcal/kg cl
$L_{min,\ Heat}$ = Minimum combustion air (from $L_{min,\ Heat}$ table) .... kg/1000 kcal
NB!! When calculating Primary Air % in kiln burner remember to use heat consumption in kiln only.

Table for Minimum Combustion Air $L_{min,\ Heat}$ and combustion products (Empirical Values)

	Units	Oil/Petcoke	Coal		Nat.Gas
L_{min}			Lignite	Standard Coal/Anthracite	
Combustion Air	kg/1000 kcal	1,41	1,39	1,42	1,43
Combustion Air	Nm^3/1000 kcal	1,09	1,07	1,10	1,10
Combustion products					
Combustion gases	Nm^3/1000 kcal	1,16	1,12	1,17	1,22
Comb, gases specific weight	kg/Nm_3	1,302	1,35	1,34	1,24
NB! In addition to the combustion gases, it may be appropriate to include some fraction of CO_2 gas from calcination. approx. 0,55 kg CO_2/kg cl. or 0,278 Nm^3/kg cl					

Data: Fuel ....Oil
Heat Consumption.................683,7 kcal/kg cl
% fuel to Kiln........................41,7%
Prim. Air amount (measured)6666,7 kg/h
Oil consumption....................11652 kg/h.

Production .... 4000 tpd
% fuel to Calc................ 58,3%
$L_{min,Heat}$ (see table)......... 1,41 kg Air/10^3 kcal
H_i Oil. .... 9780 kcal/kg

Results:

$$L_{min,Flow} = \frac{1,41 \times 683,7 \times 4000}{24} = 160.669 \text{ kg/h}$$

$$L_{min,Flow} = 1,41 \times 11,652 \times 9780 = 160.678 \text{ kg/h}$$

$$L_{min,\,Heat} = \frac{1000 * L_{min,\,Fuel}}{H_{i,\,Fuel}}$$

	Units	Oil/Petcoke	Coal		Nat.Gas
Combustion gases	Nm^3/1000 kcal	1,16	1,12	1,18	1,22
Comb, gases specific weight	kg/Nm_3	1,302	1,35	1,35	1,24

Calculating the Minimum Combustion Air ($L_{min,\,Fuel}$) from oil or coal analysis.

The minimum combustion air requirement of 1 kg fuel can be calculated from an ultimate fuel analysis %C(carbon), %H(hydrogen), %O(oxygen), %S(sulphur) and %N(nitrogen). The density of atmospheric air is 1,293 kg/Nm^3 and the density of oxygen is 1,429 kg/Nm^3. Atmospheric air contains approx. 21 % *oxygen* and the remainder is taken as 79 % *nitrogen*.

$$L_{min,Fuel} = \frac{1,293}{1,429 * 21}\left(\frac{32}{12}\%C + \frac{16}{2}\%H - \%O + \%S + \frac{32}{14}\%N\right) kg\ \ Air/kg\ \ fuel$$

Example: A fuel oil analysis is given as 85,2 %C, 11,60 %H, 0,2 %O, 0,90 %N, 2,10 %S.

$$L_{min,Fuel} = \frac{1,293}{1,429 * 21}\left(\frac{32}{12}\times 85,2 + \frac{16}{2}\times 11,6 - 0,2 + 2,1 + \frac{32}{14}\times 0.9\right) = 13,96 \text{ kg Air/kg oil}$$

Calculating the Minimum Combustion Air ($L_{min,\ fuel}$) when gas analysis is known.

$$L_{min,\ fuel} = \left\{ ½(CO + H_2) + 2CH_4 + \sum \left(n + \frac{m}{4} \right) C_n H_m - O_2 \right\} \times \frac{100}{21}\ Nm^3_{air}/Nm^3_{gas}$$

Calculation sample

Sample analysis
Natural gas
CH_4 ...... 91,1%
C_2H_6 .... 4,7%
C_3H_8 .... 1,7%
C_XH_Y ...... 1,4 %
N_2........... 0,6%
CO_2 .... 0,5%
O_2 .... 0,0%

$$L_{min,fuel} = \left\{ \frac{1}{2}(CO + H_2) + 2CH_4 + \left(3 + \frac{8}{4} \right) C_3H_8 + \left(2 + \frac{6}{4} \right) C_2H_6 + \left(4 + \frac{10}{4} \right) C_4H_{10} - O_2 \right\} \times \frac{100}{21}\ Nm^3_{air} / Nm^3_{gas}$$

$$L_{min,fuel} = \left\{ \frac{1}{2}(0+0) + (2 \times 0{,}911) + \left(3 + \frac{8}{4} \right) 0{,}017 + \left(2 + \frac{6}{4} \right) 0{,}047 + \left(4 + \frac{10}{4} \right) 0{,}014 - 0 \right\} \frac{100}{21} = 10{,}3\ Nm^3_{air} / Nm^3_{gas}$$

Volume (Nm^3) of combustion products of 1 kg fuel with excess air:

$$\mathbf{V_{min}} = (\mathbf{1{,}855 \times C}) + (\mathbf{0{,}6841 \times S}) + (\mathbf{0{,}8 \times N_2}) + (\mathbf{1{,}244 \times H_2O}) + (\mathbf{11{,}21 \times H_2}) + (\mathbf{0{,}79 \times L_{min,fuel}} \times \lambda)$$

(Lambda ? excess air coefficient see G-4)

Excess Air Coefficient (λ)

To compensate for the inadequate mixture of air and fuel even in the best burner excess air is required for complete combustion. This is normally indicated by the " Excess Air Coefficient" Lambda (λ).

$$\lambda = \frac{L_{\text{total Flow}}}{L_{\text{min Flow}}} \qquad\qquad L_{\text{Total Flow}} = \lambda \times L_{\text{min Flow}}$$

By analysing the kiln gas for O_2 and CO_2.With an orsats, or other instrument. Lambda (λ) can be calculated as followed:

$$\boxed{\lambda = \frac{1}{1-\left(\frac{79}{21}\times\frac{O_2}{100-CO_2-O_2}\right)}}$$

If CO is Present then:

$$\boxed{\lambda = \frac{21}{21 - 79 \times \left(\frac{O_2 - (0{,}5 \times CO)}{100 - CO_2 - O_2 / CO}\right)}}$$

<u>If no CO_2 Analyser is available use following Thumb Rule</u>:

Kiln Inlet : $\lambda = \left(\frac{6 \times O_2}{100}\right) + 1$ ***Preheater Outlet:*** $\lambda = \left(\frac{7 \times O_2}{100}\right) + 1$

The table below is a calculation of the heat loss compared to the amount of excess air

Excess air %	0_2 [%]	CO_2 [%]	Lost Heat [kcal/kg cl]	CO [%]
10	1,6	32,2	8	-
20	3,0	29,3	16	-
30	4,2	27,7	25	-
40	5,1	27,3	33	-
50	6,0	26,3	41	-
60	6,8	25,0	49	-
0	0,0	-	40	1,0

Table:2

For every 0,1 % CO, the heat loss is approximately 4 kcal/kg clinker

Table for Combustion Products

Table: 3

% Excess Air	% O_2	Smoke Gas Density kg/Nm^3			
			Coal		
		Oil	Coal 5 – 40% Vol.	Lignite 53 – 56 %Vol.	Natural Gas
0	0	1,303	1,354	1,347	
5	1	1,302	1,351	1,345	
10	2	1,302	1,348	1,343	
15	2,7	1,302	1,345	1,341	
20	3,5	1,302	1,343	1,339	
25	4,2	1,301	1,341	1,337	
30	4,9	1,301	1,339	1,335	
35	5,4	1,301	1,337	1,334	
40	6,0	1,301	1,336	1,333	
45	6,5	1,300	1,335	1,332	
50	7,0	1,300	1,334	1,331	

NB! In addition to the combustion gases, it may be appropriate to include some fraction of CO_2 gas from calcination. Approx. 0,55 kg CO_2/kg cl. or 0,278 Nm^3/kg cl

Table:4

Type of gas	Chemical Formular	Cp:0 – 400 °C (kcal/kg °C)	Specific Volume (Nm^3 /kg)	Specific weight (kg/Nm^3)
Amb.Air	-	0,246	0,773	1,293
Oxygen	O_2	0,231	0,700	1,429
Nitrogen	N_2	0,253	0,800	1,250
Hydrogen	H_2	3,463	11,117	0,090
Carbon monoxide	CO	0,254	0,800	1,250
Carbon Dioxide	CO_2		0,506	1,977
Steam	H_2O	0,236	1,244	0,804
Sulphur dioxide	SO_2		0,342	2,926
Ammonia	NH_3	0,463	0,771	0,771
Methane	CH_4	0,169	1,397	0,717
Methanol	CH_3OH		0,699	1,430
Methyl Chloride	CH_3Cl		0,562	2,307
Ethane	C_2H_6		0,745	1,356
Acetylene	C_2H_2		0,861	1,171
Ethylene	C_2H_4		0,799	1,261
Ethanol	C_2H_5OH		0,486	2,056
Propane	C_3H_8		0,509	1,968
Butane	C_4H_{10}		0,386	2,594
Pentane	C_5H_{12}		0,311	3,219
Hexane	C_6H_{14}		0,260	3,844
Acetone	C_3H_6O		0,385	2,592

Air and gas calculations

The equation of the state of an ideal gas: $\frac{p \times V}{T} = n \times R$

Where: $\mathbf{n = mol}$

$\mathbf{R = 0.08206} \left(\frac{liter \times atm}{{}^{o}K \times mol}\right)$

Temperature and pressure for the standard reference state also called the normal state
The reference state of a gas is at 0° C and 1 atm

Temperature	Pressure
0° Celsius	1 atm
273.15 °Kelvin	1013.25 hPa
32 °Fahrenheit	760 mmHg(Torr)

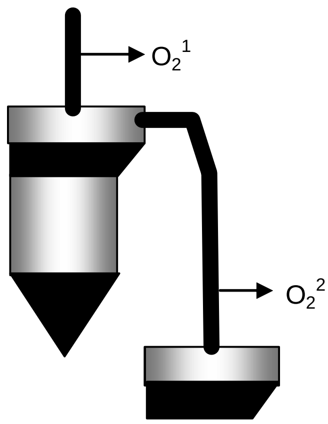
$$V_1 = V_0 * \frac{273°C}{(273°C + T_1)} * \frac{P_1}{1013\,hPa}$$

False Air Quantity 1

Calculation of False Air between two points using O_2 Gas Analysis Measurements

Measure O_2^1 and O_2^2

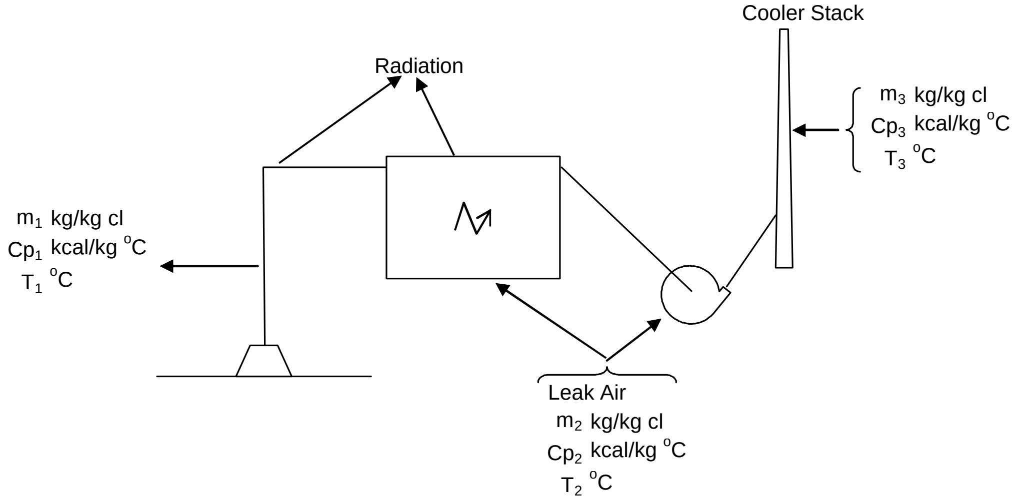
$$\textbf{\% False Air} = \left(100 \times \frac{21 - O_2^{1}}{21 - O_2^{2}}\right) - 100$$



E.g: Measured at cyclone inlet O_2 = 2,4, after cyclone O_2 = 3,9

$$\left(100 \times \frac{21 - 2,4}{21 - 3,9}\right) - 100 \approx 8,8\ \%\ \text{False Air}$$

False Air Across Cooler Filter



When effective leak air measurements cannot be obtained, the amount of leak air can be calculated knowing the temperature of the gas in, the mass and the temperature of the gas out, and the temperature of the leak air by the following:

1. gas inlet condition
2. leak air inlet condition
3. gas outlet condition

$$m_1 + m_2 = m_3$$

$$m_1 C_{p1} T_1 + m_2 C_{p2} T_2 = m_3 C_{p3} T_3 + RAD$$

Solving two equations for the leak air m_2 gives

$$m_2 = \frac{m_3 \left(C_{p1} T_1 - C_{p3} T_3 \right) - RAD}{C_{p1} T_1 - C_{p2} T_2}$$

The radiation (RAD) is often minimal and can normally be neglected.
For calculation of ean Specific Heat see calculation page **H-2** or table page **M-4**

<u>Below is a formula which can be used to estimate amounts of false air at openings</u>

The gas escaping through a sharp edged hole, in a thin wall is approx. 61% of the gas escaping a similar area under”loss free” conditions.

$$\mathbf{Q = 0{,}61 * F * \sqrt{2 * Dp * 100} \quad (m^3/s)}$$

$$\boxed{\mathbf{Q = F * \sqrt{74{,}42 * Dp} * r \quad (kg/s)}}$$

$\mathbf{Dp}$ **Pressure difference mbar**

r **Density kg/m^3**

F cross section m^2

Approximate Gas Velocity Calculation

E.g. through kiln riser pipe.

Measured In Riser

O_2 .... 4,3 %
CO_2 .... 18,6 %
T_{riser} .... 1150 ^oC
P_{riser} .... 735 mmHg
Area $_{cross\ section}$ ..... 4,021 m^2

Loss of Ignition

Mat. To Riser…5 %
Kiln Feed........... ….34,9 %

Data & Calculations

Production.........4000 t/d
Heat Cons.Kiln..285,4 kcal/kg
Fuel Cons.Klin..4864 kg/h
T_{amb} ....20 ^oC
P_{amb}....................737 mm
$\%_{Moisture}$ ....70 %

$L_{min\ Flow}$ ....67259 kg/h (calculated)
λ ....1,2655 (Calculated)

Fuel Contribution.

The fuel is considered as completely burnt out.

$m_{gas.fuel}$ $\quad$ ***= 4864 kg/h***

Combustion air Contribution.

Combustion air includes primary air, secondary air and false air.

$$m_{comb.air} = L_{min\ Flow} \times \lambda = 67259 \times 1{,}2655 = 85117{,}3\ kg/h$$

CO_2 Contribution

$$m_{gasCO_2} = \frac{LOI_{riser}}{100 - LOI_{riser}} \times \frac{Prod}{24}$$

$$m_{gasCO_2} = \frac{5}{100 - 5} \times \frac{4000}{24} = 8771{,}9\ \ kg/h$$

Total mass of gas in riser pipe.

$$m_{Total} = m_{gas,\,fuel} + m_{comb.air} + m_{gas\,,CO2}$$

$$m_{Total} = 4864 + 85117{,}3 + 8771{,}9 = 98813{,}2 \;\; kg/h$$

Calculation of Gas Velocity

The approximate density of the combustion gas and CO_2 is found on pages ***G5 table 3 and G5 table 4***

$\rho_{comb,gas} = 1{,}302\ kg\ /Nm^3$ $\qquad\qquad$ $\rho_{CO2} = 1{,}977\ kg\ /Nm^3$

$$\rho = \frac{98813{,}2}{\left(\frac{4864 + 85117}{1{,}302}\right) + \left(\frac{8771{,}9}{1{,}977}\right)} = 1{,}343 \;\; kg\ /Nm^3$$

Calculated density of gas at temperature 1150 ^{o}C and pressure 735 mmHg:

$$\rho_{1150,735} = 1{,}343 \times \frac{273}{273 + 1150} \times \frac{735}{760} = 0{,}249 \quad kg/m^3$$

Gas flow through riser pipe:

$$Q_{riser} = \frac{m_{Total}}{\rho_{1150,735}} \left[m^3 / s\right]$$

$$Q_{riser} = \frac{98813{,}2}{0{,}249} = 394835\ m^3/h \approx 110{,}23 \quad m^3/s$$

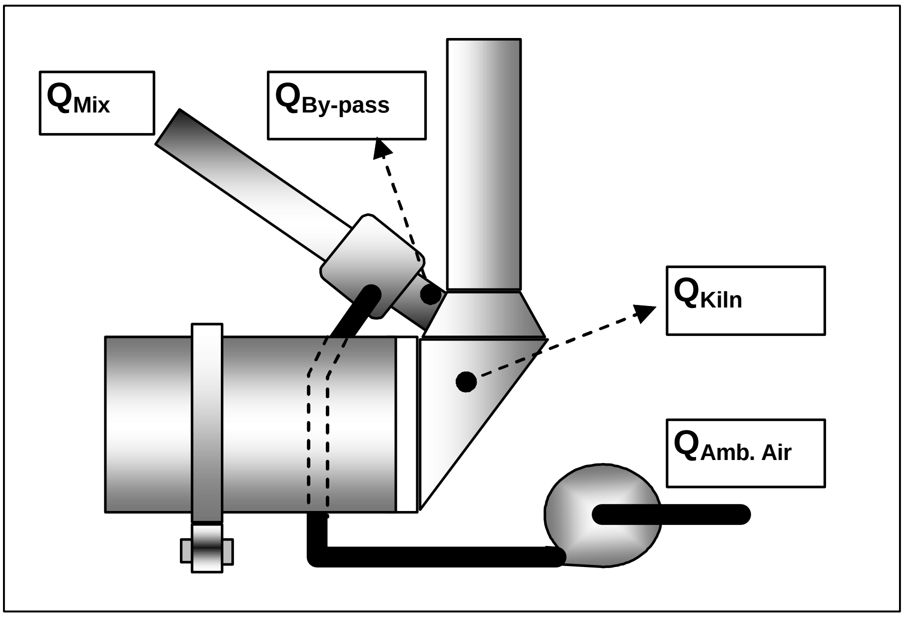
Gas Velocity in the riser pipe:

$$v_{riser} = \frac{Q_{riser}}{A_{riser}} \;\; \left[m / s\right]$$

$$v_{riser} = \frac{110{,}2}{4{,}021} = 27{,}4\ m/s$$

The Kiln Gas By-Pass

A kiln gas By-Pass is used to take out volatile matter that circulates and accumulates in the hot regions of the kiln. A fraction of the kiln gases sufficient to maintain stable operating conditions is taken out and cooled. The fraction depends on the volatiles entering the kiln system with raw materials and fuels. The volatile matter in the By-Pass gas such as chloride, sulphate and alkalies is separated with a filter.



To calculate the %By-Pass it is necessary to find the kiln gas (Q_{KILN}) and the By-Pass gas ($Q_{BY\text{-}PASS}$). The kiln gas is calculated with the following information: (see also G8-G9)

Q_{KILN}[kg/h] = Fuel x (1-Ash) + Combustion air (with O_2 kiln inlet) + CO_2(in hot meal)

The By-Pass gas is calculated from the following mass- and energy balance equations:

Where: c_1 and c_2 are the Specific Heat of the Gases

$$Q_{BY\text{-}PASS} + Q_{AMB.\ AIR} = Q_{MIX}$$

and

$$Q_{BY\text{-}PASS} \times c_1 \times (T_{INLET} - T_{MIX}) = Q_{AMB.\ AIR} \times c_2 \times (T_{MIX} - T_{AMB})$$

Solving the equations gives the following:

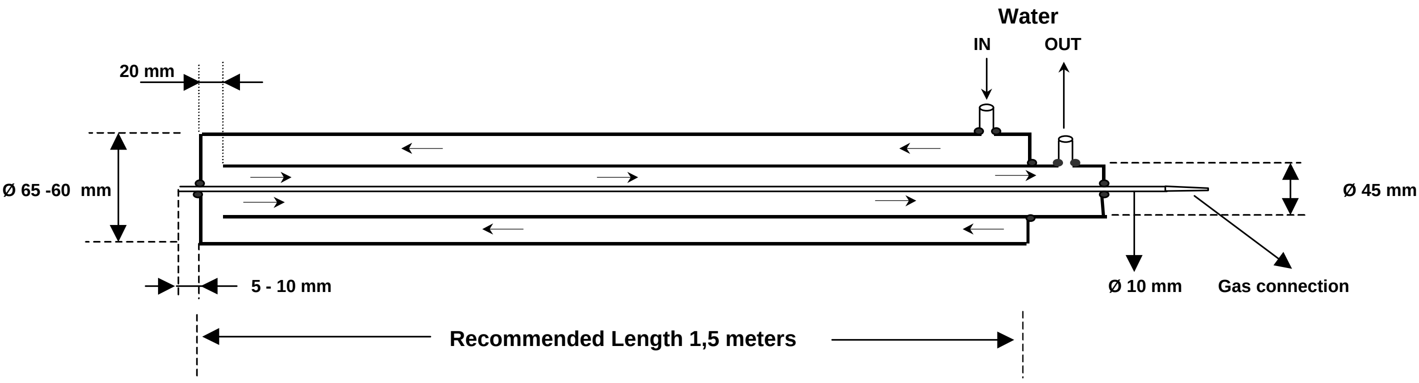
$$Q_{BY-PASS} = Q_{MIX} \times \left(\frac{c_2 \times (T_{MIX} - T_{AMB})}{c_1 \times (T_{INLET} - T_{MIX}) + c_2 \times (T_{MIX} - T_{AMB})} \right) \approx Q_{MIX} \times \left(\frac{T_{MIX} - T_{AMB}}{T_{INLET} - T_{AMB}} \right) [kg/h]$$

%By-Pass = $Q_{By\text{-}Pass}/Q_{kiln}$ x 100%

Water cooled Gas analysing probe.

Due to the very high temperature in the kiln inlet, and low stages of the preheater. It is recommended to use a water cooler probe to extract a reliable sample from these mention areas .

Following is a sketch of such a probe which can be fabricated on site.



Cooling water consumption ~ 15 l/min

Volume Flow (Q)

The volume flow of gas at 0 ^oC and 10333 mmWG = Q_N (Nm^3/h)

The volume flow of gas at t ^oC and B mmWG = Q (m^3/h)

$$\mathbf{Q = Q_N \times \frac{273 + t}{273} \times \frac{10333}{B \pm P_s} \quad [m^3/hr]}$$

The barometric pressure, B, in the following equation depends on the altitude (m)

$$B = 760 * e^{-0,0001255 \text{ x } H} \ \textit{(mmHG)} \qquad \text{or} \qquad B = 10333 * e^{-0,0001255 \text{ x } H} \ \textit{(mmWG)}$$

P_s = Static pressure *(1 mmHG = 13,6 mmWG @ 0 ^0C)*

Density (ρ):

The density of a gas at 0 ^oC and 10333 mmWG = ρ_N (kg/Nm^3)

The density of a gas at t ^oC and B mmWG = ρ (kg/m^3)

$$\rho = \rho_N \times \frac{\mathbf{273}}{\mathbf{273 + t}} \times \frac{\mathbf{B \pm P_s}}{\mathbf{10333}} \quad [\mathbf{kg/m^3}]$$

$$\rho_N = \frac{\textbf{Molar weight}}{\mathbf{22,4}} \quad \left[\frac{\mathbf{kg/kmol}}{\mathbf{Nm^3/kmol}}\right] \approx [\mathbf{kg/Nm^3}]$$

where 22,4 ($Nm^3/kmol$) is the standard molar volume of any gas.

Specific Heat (C_p)

The specific heat, C_p (kcal/kg ^oC), is the energy required to heat 1 kg of a specific material 1^oC

To heat G (kg) of a material with a specific heat C_p from t_1 to t_2 (^oC) requires:

$$H = C_p \times G \times (t_2 - t_1) = [kcal]$$

Mean specific heats between 0 and t ^oC and 32 and t ^oF

$$\text{Specific heat} = A + (B \times t \times 10^{-6}) + (C \times t_2 \times 10^{-9}) = kcal/kg\ ^oC$$

$$\text{Specific heat} = A + (B \times (t - 32) \times 10^{-6}) + (C \times (t - 32)^2 \times 10^{-9}) = BTU/lb\ ^oF$$

	Metric Units			US Units		
	A	**B**	**C**	**A**	**B**	**C**
CO_2	0,196	118	-43	0,196	66	-13,2
H_2O	0,443	39	28	0,443	22	8,6
N_2	0,244	22	0	0,244	12	0
O_2	0,218	30	0	0,218	17	0
Air	0,237	23	0	0,237	13	0
Raw meal	0,206	101	-37	0,206	56	-11,4
Clinker	0,186	54	0	0,186	30	0
Coal	0,262	390	0	0,262	217	0

Table for specific heats see page M-4

Heat of Evaporation

(for water at 100 ^oC)

The heat of evaporation is the amount of heat it takes to turn 1 kg of water at 100 ^oC into steam at the same temperature. The heat of evaporation for water (H_{evap}) is 540 kcal/kg.
To evaporate1 kg of water at 0 ^oC into steam at 100 ^oC requires a total heat of:

$$H = \left[C_p \times G \times (t_2 - t_1) + (G \times H_{evap})\right] \quad = \text{total heat}$$

$$H = \left[1\ kcal/kg\ ^oC \times 1\ kg \times (100\ ^oC - 0\ ^oC)\right] + (1\ kg \times 540\ kcal/kg) \quad = 640\ kcal$$

Thermal Conduction

The coefficient of thermal conduction (ε) is the unit rate of thermal load (kcal/m^{2}hr^{o}C) that moves through a 1 meter thick plate of material, when the surface temperature difference i 1 ^{o}C.

Below is a list of approximate conductivity's for some insulated materials:

Special clay *(Moler)* :	0,16	kcal/m^{2}hr^{o}C
Alumina *(Chamotte)* :	0,65 – 0,75	kcal/m^{2}hr^{o}C
Air :	0.30	kcal/m^{2}hr^{o}C
Kiln Shell	40	kcal/m^{2}hr^{o}C

Radiation Loss

Radiation as it appears in a cement plant is usually a combination of radiation and convection calculated as follows:

RADIATION $= 4 \times 10^{-8} \times \left(T^4 - T_f^4\right) \quad \mathrm{kcal/h \cdot m^2}$

CONVECTION $= 80{,}33 \times \left(\frac{T + T_f}{2}\right)^{-0{,}724} \times \left(T - T_f\right)^{1{,}333} \quad \mathrm{kcal/h \cdot m^2}$

T is the surface temperature in *Degree Kelvin*
Tf is the ambient temperature in *Degree Kelvin*

If the measured surface is exposed to wind above 3m/s, the convection is called forced convection and should calculated according to:

FCON $28{,}03 \times \left(T \times T_f\right)^{-0{,}351} \times V^{0.805} \times D^{-0{,}195} \times \left(T - T_f\right) \; \mathrm{kcal/h \cdot m^2}$

V is the wind speed in m/s
D is the of the measured object (kiln) in m.

$$\textbf{Specific Radiation} = \frac{\mathrm{kcal/h}}{\mathrm{area}} = \mathrm{kcal/h \cdot m^2}$$

$$\textbf{Specific Surface} = \frac{\mathrm{Area}}{\mathrm{kgcl/h}} = \mathrm{m^2/(kg\ cl \cdot h)}$$

$$\textbf{Total Radiation} = \text{spec.surface} \times \text{spec.radiation} = \mathrm{kcal/kg}$$

Clinker Factor

(For Oil and Gas & firing w. Dust to Silo)

$$\text{Prod.} = \text{Feed} \times \left(1 - \frac{LOI_{feed}}{100}\right) \times \left(1 - \frac{H_2O_{freel}}{100}\right) \times \left(1 - \frac{\text{Dust Loss}}{100}\right)$$

(For Coal & Petcoke Firing w. Dust to Silo)

$$\text{Prod.} = \text{Feed} \times \left(1 - \frac{LOI_{feed}}{100}\right) \times \left(1 - \frac{H_2O_{free}}{100}\right) \times \left(1 - \frac{\text{Dust Loss}}{100}\right) + \left(\frac{\text{coal input} \times \%\ \text{ash in coal}}{100}\right)$$

LOI_{feed} at 950 ^oC includes $C_{organic}$, H_2O_{bound} and CO_2

$H2O_{free}$ = free moisture

Normally expected dust loss from preheater is 7 – 10 %

Fan Power (Dust Free)

$$N_{Fan(Dustfree)} = \frac{Q \times p_t}{\eta} \frac{9.81}{1000} = \quad kW$$

Where:

$Q = m^3/sec$
$p_t = p_d + p_s$ = mmWG
η = **Efficiency 60 – 80** %

Burner Nozzle Velocity

(For quick calculation of flame momentum with reasonable accuracy)

$$v \approx 4\sqrt{P_s} \quad m/s \quad (P_s \text{ in mmWG})$$

$$v \approx \sqrt{\frac{200 \times P_s}{\rho}} \quad m/s \quad (P_s \text{ in mbar})$$

P_s measured at axial air pressure point
ρ **= Density**

NO_x and SO_x Conversion

Converting measured ppm NO_x ***OR*** SO_x at the actual O_2 level to NOx ***or*** SOx at 10 % O_2 .

$$\textit{Measured ppm}_{NO_x} \textit{ or ppm}_{SO_x} \times \frac{21 - 10}{O_2} = ppm_{NO_x} \textit{ or ppm}_{SOx} \textit{ at 10 \% } O_2$$

Convert ppm to mg NO_2 or SO_2 /Nm^3

$$\mathbf{mg\ NO_2/Nm^3 = ppm\ NO_x\ x\ 2{,}05}$$
$$\mathbf{mg\ SO_2/Nm^3 = ppm\ SO_x\ x\ 2{,}86}$$

Example:

600 ppm NO_x measured at 3 % O_2

$$600 \times \frac{21-10}{21-3} = \quad 366{,}67 ppm \text{ at } 10 \ \% \ O_2$$

Coal firing transport

In order to assure pulse free pneumatic transport of pulverised coal

- Coal to transport air ratio at max. consumption $\leq$ 4 kg coal/kg air.
- Back pressure in pipeline for screw transport $\leq$ 54 kPa
- Back pressure in pipeline for phister feeder $\leq$ 40 kPa
- Transport velocity v (m/s) $\leq 66 \text{ x}(D_i)^{½}$ (28.33 m/s)
- D_i = inner diameter in (m)
- Max. transport length 150 m
- Transport Air speed at burner Tip ~30 m/sec

Pipe lines must be horizontal and vertical only with as few 90^o bends as possible

Clinker Particle Size Distribution

Clinker size distribution is done by stopping the clinker tranport after reject bin. Remove all the clinker + dust from two to three buckets or min 1 meter of the clinker in a pan conveyor. Sieve the whole sample though a number sieves between 0,5 to 40mm.
Plot the residue from each sieve into the curve on page **N-1**

eg:

Sample ID:

Size (mm)	0,5	1	2	4	8	16	25	40
% residue	98,1	97,7	96,8	94,5	83,5	60,8	34,7	14,4

Effects of Production increase

1. *The Pressure at the preheater outlet increases in relation to the production as shown below:*

$$\mathbf{mbar_1 \times \left(\frac{Pr\,od._2}{Pr\,od._1}\right)^2 = mbar_2}$$

Example:

Production = 3300 t/d , Pressure = 43 mbar

Production Increase = 3500 t/d, Pressure = 48 mbar

$$43 \times \left(\frac{3500}{3300}\right)^2 = 48 \text{ mbar}$$

2. *The ID Fan Power increases in relation to the Production as shown below:*

$$\mathbf{kW_1 \times \left(\frac{Pr\,od._2}{Pr\,od._1}\right)^3 = kW_2}$$

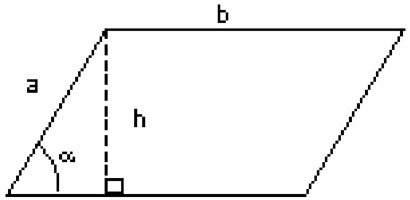
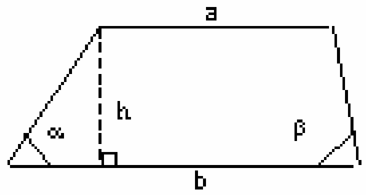
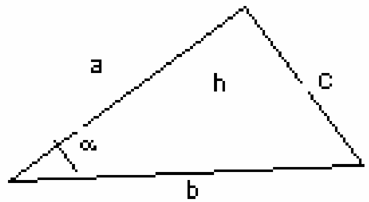
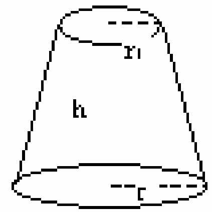
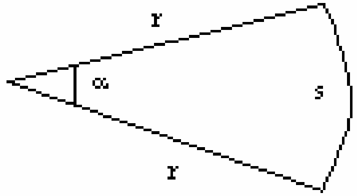
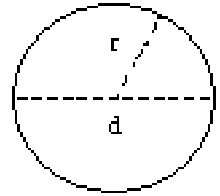
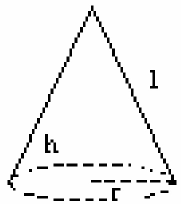
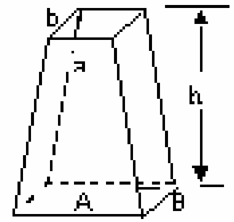
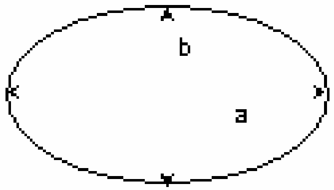
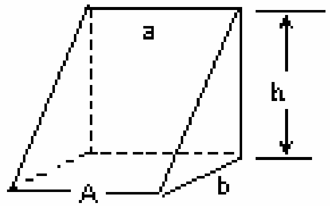
Example:

Production = 3300 t/d , KW = 580

Production Increase = 3850 t/d , Kw = 920

$$580 \times \left(\frac{3850}{3300}\right)^3 = 920 \text{ kW}$$

3. *Gas Flow increases with the same ratio as the Production.*

$\text{Area} = b \times h = a \times b \times \sin\alpha$ $\text{Cir.} = 2a \times 2b$ 	$\text{Area} = 0{,}5\,h \times (a + b)$ $\text{Cir.} = a + b + h \times \left(\frac{1}{\sin\alpha} + \frac{1}{\sin\beta}\right)$ 
$\text{Area} = 0{,}5b \times h = 0{,}5a \times b \times \sin\alpha$ $= \sqrt{s(s-a)\times(s-b)\times(s-c)}$ $s = 0{,}5(a + b + c)$ $\text{Cir.} = a + b + c$ 	$\text{Vol.} = \frac{1}{3}\pi \times h \times (r^2 + r \times r_1 + r_1^2)$ $\text{Curved Surface} = \pi \times l \times (r + r_1)$ $= \pi \times (r + r_1) \times \sqrt{h^2 + (r - r_1)^2}$ 
$\text{Area} = 0{,}5 \times r^2 \times \alpha$ 	$\text{Area} = \pi \times r^2 = \frac{\pi}{4} d^2$ $\text{Cir.} = 2 \times \pi \times r$ 
$\text{Vol.} = \frac{1}{3}\pi r^2 h$ $\text{Curved surface} = \pi \times r \times l$ $= \pi \times \times \sqrt{r_2 + h^2}$ 	$\text{Vol.} = \frac{h}{6} \times [(2A + a) \times B\,(2a + A) \times b]$ 
$\text{Area} = \pi \times a \times b$ $\text{Cir.} = 2\pi \times \sqrt{\frac{1}{2 \times (a^2 - b^2)}}$ 	$\text{Vol.} = \frac{1}{6} h \times b \times (2A + a)$ 

This PID regulator adjusting method (Heilmanns method) explains a way which leads the user to set regulator parameters, **which will only be as good as his patience,** this means that one has to try the adjusting more than once.

PID Control Expressions

$\textbf{gain} = \frac{\textbf{100}}{\textbf{prop .band}}$, ® $\textbf{prop .band} = \frac{\textbf{100}}{\textbf{gain}}$

Proportional gain = 1, $\rightarrow$ prop.band = 100: (K_p)

time = 12 sec $\rightarrow$ minute/rep = 5, $\rightarrow$ rep/min = 0,20 (T_n , T_i)

Derivative time (T_d, T_v)

Process Value (PV)

Finding an estimate for a reset time T_n (Integral time T_i)

1) First priority is get an impression of the open loop time of reaction τ. Place the regulator in Manual mode, make a reasonable step change of the regulator set-point SP, just enough to observe a clear reaction on the PV signal.

2) The open loop PV signal is typically a signal like the one shown on the graph fig 1. possibly with an overshoot.

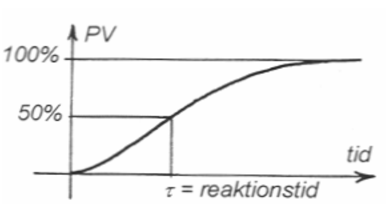


Fig. 1

t =**Reaction Time**

3) Observe the PV signal curve, and note the time for a 50 % change of the total change, as in above graph fig. 1. This time will now be used as temporary value for the reset time T_n.

4) The regulator Proportional gain has to be adjusted to minimum. Adjust manually the process to a normal working value and switch the regulator to Auto mode.

5) Now the Proportional gain has to be adjusted. By increasing the gain and making changes to the set-point around the normal working value, observe the PV signal. When the gain adjustment is just high enough to make a slight overshoot as illustrated in the graph fig 2, we have a reasonable set-up parameter for the PI-loop.

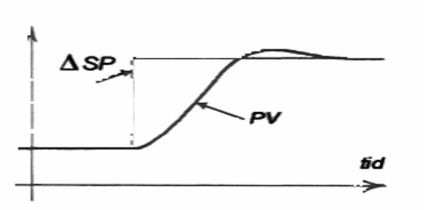


Fig. 2

6) Now it is time for the Derivative Time Td to be adjusted, **if needed.** Again by making changes to the setpoint and changes to the Td settings to the PV signal is observed. Quite often T_d adjustment will make a overshoot disappear. The D-influence acts as a dampening factor on the loop. This again is compensated for by increasing the gain K_p, until a little overshoot again is observed, again the T_d is adjusted until the overshoot is lowered. This action is continued until no more improvement is observed. Often the T_d action will make it possible to lower the T_n .
If the loop becomes “ nervous” with a small setting of the T_d, it could be a noise problem, and a filtering of the signals could be tried. If this is do not help, then don’t use the T_d function at all.

Analysis of Kiln Downtime

Productivity:

$$Productivity = \frac{Actual\ production}{Maximum\ production}$$

(Acceptable approx. level ≥ 0,80)

The maximum production of the period in question should be calculated as the number of days times the maximum sustainable production rate.

The maximum sustainable production rate is generally agreed upon as the maximum kiln output during a 24 hour period, which normally is somewhat higher than output given by the supplier.

Time Run Factor:

$$Time\ Run\ Factor = \frac{Actual\ Running\ Time}{Total\ Time}$$

(Acceptable approx. level ≥ 0,85)

Total time is the time units of the period in question without deductions.

Production factor:

$$Production\ Factor = \frac{Actual\ Production}{Theoretical\ Production}$$

(Acceptable approx. level ≥ 0,95)

Theoretical Production is what should have been produced in the time available, i.e. production rate times actual running time.

The two factors are connected in the following manner:

$$Productivity = Time\ Run\ Factor \times Production\ Factor$$

Thermocouple Type:

Thermocouple Type	Names of Materials	Useful Application Range
B	Platinum30% Rhodium (+) Platinum 6% Rhodium (-)	2500 -3100F 1370-1700C
C	W5Re Tungsten 5% Rhenium (+) W26Re Tungsten 26% Rhenium (-)	3000-4200F 1650-2315C
E	Chromel (+) Constantan (-)	200-1650F 95-900C
J	Iron (+) Constantan (-)	200-1400F 95-760C
K	Chromel (+) Alumel (-)	200-2300F 95-1260C
N	Nicrosil (+) Nisil (-)	1200-2300F 650-1260C
R	Platinum 13% Rhodium (+) Platinum (-)	1600-2640F 870-1450C
S	Platinum 10% Rhodium (+) Platinum (-)	1800-2640F 980-1450C
T	Copper (+) Constantan (-)	-330-660F -200-350C

Thermal load for FLS standard kiln systems		
Kiln system	Volumetric load [tpd/m^3]	Burning zone load [10^6 kcal/h/m^2]
SP	1.8 - 2.3	2.8 - 5.5
ILC-E	1.8 - 2.5	2.8 - 6.0
ILC	3.6 - 4.8,usually ~4.5	2.8 - 5.5
SLC	3.6 - 4.8,usually ~4.5	2.8 - 5.5
SLC-I	3.6 - 4.8,usually ~4.5	2.8 - 5.5
SLC-S	3.6 - 4.8,usually ~4.5	2.8 - 5.5
SLC-D	3.6 - 4.8,usually ~4.5	2.8 - 5.5
ROTAX	max 5.0 + 0.3 [3,6 - CaOfree,1400 C] with upper limit: 5.3	2.5 - 5.3

Symbols:

P	=	Kiln Production in (tons/24h)
L	=	Length of Kiln in (m)
H	=	Kiln inclination in (%)
O	=	Kiln speed in (rpm)
D_i	=	Kiln inside Diameter in (m)
L_{Vol}	=	Volumetric load in (tpd/m^3)
P_ω	=	Kiln power consumption

$$L_{Vol}\left[tpd/m^3\right] = \frac{P}{\pi \times \frac{D_i^2}{4} \times L}$$

Burning Zone Filling Degree

$$F\left[\%\right] = \frac{3{,}2 \times P}{D_i^3 \times H \times O}$$

The length of the burning zone in SP and PC kilns is usually measured to approx. 6,5 x D_i, which together with an estimated bulk density of 1,4 t/m^3 gives the following expression for:

Burning zone residence time:

$$t\left[min\right] = \frac{325}{O \times H}$$

Burning zone filling degree and residence time can also be expressed as a function of volumetric load and length/diameter ratio of the kiln, as shown below:

$$F = \left[\%\right] = \frac{2{,}48 \times L/D_i \times L_{Vol}}{H \times O}$$

$$t\left[min\right] = \%F\,\frac{131}{L_{Vol} \times L/D_i}$$

Kiln Power Consumption

Symbols: see page **I-1**

$$\mathbf{P_w = k_c \times \frac{P \times L}{H} \quad kW}$$

where $\mathbf{k}_c$ is a constant see table below:

(for kilns with planetary cooler: $L = L_{kiln} + L_{cooler}$)

Kiln Type	$\mathbf{k}_c$ value
SP Unax	0,0044
SP Folax, Duax	0,0033
ILC-E Unax	0,0052
ILC-E Folax,Duax	0,0040
ILC	0,0040
SLC-S	0,0040
SLC	0,0040
ROTAX	0,0050

Kiln Retention Time.

$$\mathbf{t = \frac{11{,}2 \times L}{r \times D \times s} \quad min}$$

Symbols:

L = Kiln length in meters
r = kiln speed in rpm
D = effective diameter in meters
s = slope in ^{o}

Note that the accurate estimate of the kiln retention time depends upon the physical properties of the material. the slope of cyclone preheater kilns is usually 3 – 4 %

Slope ^{o} vs. %

o	1,0	1,2	1,4	1,6	1,8	2,0	2,2	2,4	2,6	2,8
%	1,75	2,09	2,44	2,79	3,14	3,49	3,84	4,19	4,54	4,89

Burner types:

Uniflow ....single channel burner
Swirlax FCO ......Original swirlax **F**olax **C**oal **O**il (fan pressure 140 mbar)
Swirlax SOG...... for **O**il and/or **G**as firing only (fan pressure 160 –250 mbar)
Swirlax SOC ......for **O**il **C**oal firing and combined firing(fan p. 160 –250 mbar)
Centrax...............for oil and coal or combined. (primary delivered by rotary blower)
Duoflex ....for all fuels (fan pressure 250 mbar)

Primary air momentum is calculated as:

$$\boxed{L_p\% \; x \; C \;\; [\%m/sec]}$$

Where:

Lp% = The primary air % of the Kiln $L_{min\ Flow}$
C = Primary air velocity at the burner nozzle

Burner type	Uniflow	Swirlax	Centrax	Duoflex
Normal Volume % L_p	15 – 20 %	10 – 15 %	4 – 5 %	6 – 8 %
Nozzle velocity C m/sec	60 – 75	125 –200	320 – 360	200-210
Fan Pressure mbar	80 - 100	120 – 250	750	250
Pipe velocity m/sec	25 – 30	25 – 30	25 – 30	25-30
Momentum % L_p *x* C %m/s	1200 -1500	1200 – 2000	1200 – 1450	1250 – 2000

Estimated Burner Nozzle Velocity

$$v \approx 4\sqrt{P_s} \quad m/s \quad (P_s \ in \ mmWG)$$

$$v \approx \sqrt{\frac{200 \times P_s}{\rho}} \quad m/s \quad (P_s \ in \ mbar)$$

P_s measured at axial air pressure point

FLS Oil Burner Types

TSFM ....Pressure atomisation with spreader modulation. Oil pressure 25 bar
OBA ....Pneumatically operated atomising burner. Oil pressure up to 10 bar

Duoflex Burner

Data:

Amb. Press. ....p_{amb} (mbar) Amb. Temp. ......t_{amb} (^oC)
Stroichiometric combustion airflow ....$L_{min\ Flow}$ (kg/s)
Primary Air Flow Measured ....m_{pr} (kg/s)
Primary Air Pressure at Nozzle ....p_N (mbar)
Primary air temperature ....t_{pr} (^oC)
Isentropic exponent for air ....$\kappa \approx 1{,}4$
Gas constant ....$R \approx 286{,}89$ (J/kgK)
Nozzle coefficient: ....k_N
Nozzle area .... A_{Ni} (mm^2)

Comments:
The Nozzle coefficient $\boldsymbol{k_N}$ *can be found in the Burner PD diagram*
($k_N \approx 0{,}95$ *(for 100% axial air, lower with swirl).*

The Nozzle area A_{Ni} *can be found in the burner drawing according to the nozzle opening.*

Primary air percentage: $$L_p = \frac{m_{pr}}{L_{min\ Flow}} \times 100\ [\%]$$ ***(*** $\boldsymbol{L_{minFlow}}$ ***: See page G1)***

Nozzle Velocity: $$c_{pr} = \sqrt{\frac{2k}{k-1} \times R\left(t_{pr} + 273{,}15\right) \times \left[1 - \left(\frac{p_{amb}}{p_{amb} + p_N}\right)^{\frac{k-1}{k}}\right]} \quad [m/s]$$

<u>Primary Momentum:</u> $$G_{pr} = L_p \times c_{pr} \quad [\%m/s]$$

As seen nozzle area does not enter the calculations. Of course velocity can be calculated from air flow and nozzle area, but that is nor much more accurate.

First the flow function is calculated: $$y = \sqrt{\left(\frac{p_{amb}}{p_{amb} + p_N}\right)^{\frac{2}{k}} - \left(\frac{p_{amb}}{p_{amb} + p_N}\right)^{\frac{k+1}{k}}}$$

And then primary air flow:

$$m_{pr} = 10^{-4} \times A_N \times k_N \times y\left(p_{amb} + p_N\right) \times \sqrt{\frac{2k}{k-1} \times \frac{1}{R\left(t_{pr} + 273{,}15\right)}} \quad kg/s$$

These formulas apply for pressure up to approx. 890 mbar, where the speed of sound is reached

Duoflex Burner Primary Air Calculation Example

Data:

Duoflex burner type: DBC-244,5-600-9 for SP – kiln

Kiln Prod:	P	3500 tpd
Ambient pressure	p_{amb}	1013,25
Ambient temperature	t_{amb}	20 ^{o}C
Burner output:		126 MW
Stroichiometric combustion air flow	$L_{minFlow}$	41,70 kg/s
Axial damper pos.		100 % open
Radial damper pos.		50 % open
Nozzle coefficient	k_N	0,897 *(from Burner PD diag)*
Primary air press.	p_N	206 mbar
Primary air temp.	$t_{pr.}$	30 ^{o}C
Air nozzle opening		40 mm
Nozzle area	A_{Ni}	17535 mm^2 *(from drawing)*
Primary air measured	m_{pr}	180 m^3/min ~ 3,68 kg/s

Flow function:

$$\psi = \sqrt{\left(\frac{1013,25}{1013,5+206}\right)^{\frac{2}{1,4}} - \left(\frac{1013,25}{1013,25+206}\right)^{\frac{1,4+1}{1}}} = \underline{0,199}$$

Calculated primary air flow:

$$m_{pr} = 10^{-4} \times 17535 \times 0,897 \times 0,199(1013,25+206) \times \sqrt{\frac{2 \times 1,4}{1,4-1} \times \frac{1}{286,89(30+273,15)}} = \underline{3,42\, kg/s}$$

Primary air percentage: $L_p = \frac{3,42}{41,7} \times 100 = \underline{8,2\ \%}$

Primary air velocity:

$$c_{pr} = \sqrt{\frac{2 \times 1,4}{1,4-1} \times 286,89(30+273,15) \times \left[1 - \left(\frac{1013,25}{1013,25+206}\right)^{\frac{1,4-1}{1,4}}\right]} = \underline{177\ m/s}$$

<u>Primary air Momentum:</u> $G = 8,0 \times 177 = \underline{1416\ \%m/s}$

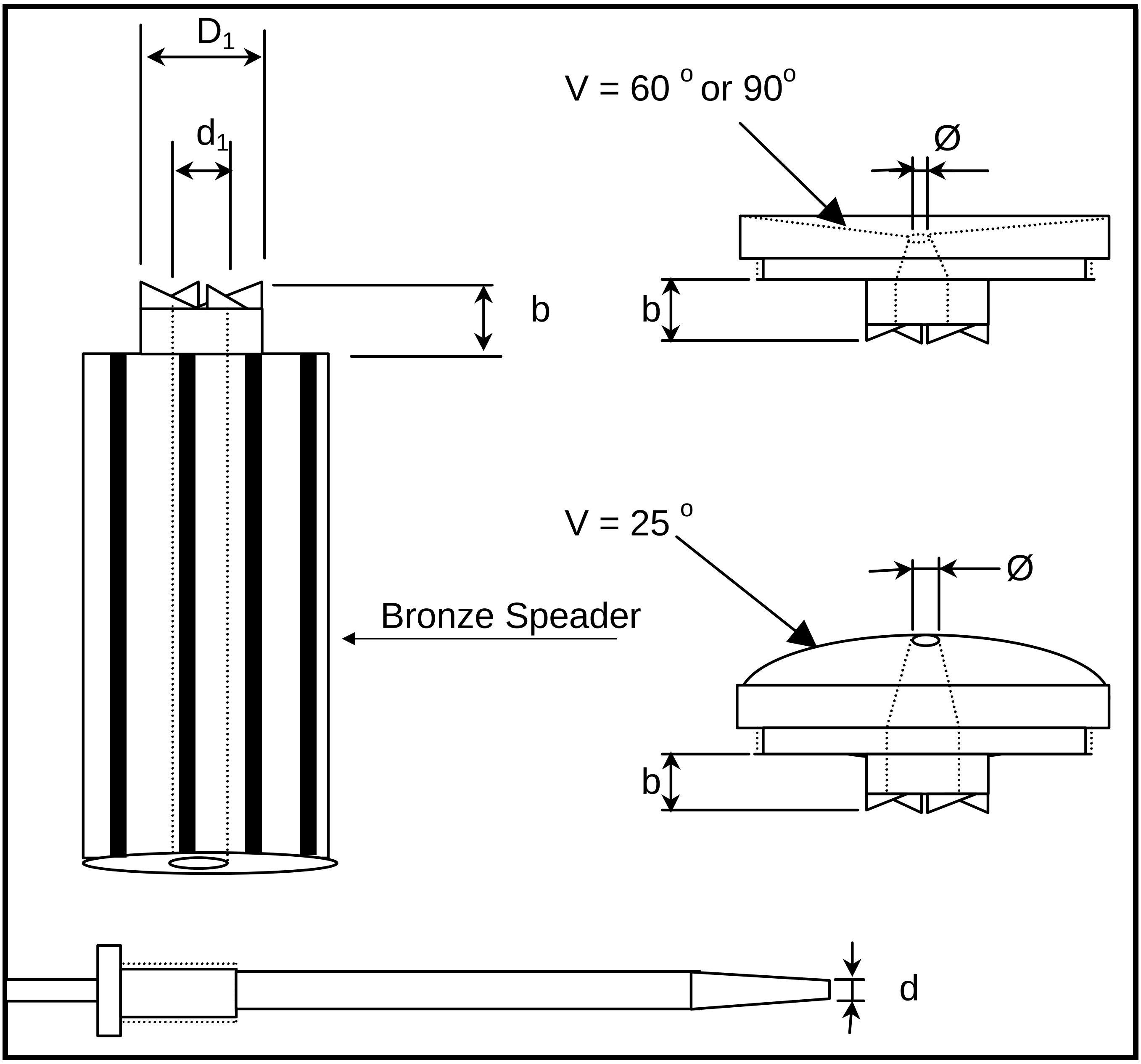
the remaining amount will be central air (for cooling thru central duct):

$$m_{central\ air} = m_{pri.air\ measured} - m_{pri.air\ calculated}$$

$$m_{central} = 3,68 - 3,42 = 0,26\ kg/s \approx \underline{0,6\ \%}$$

Total primary air, incl. central air : 8,0 + 0,6 = <u>8,6 %</u>

<table>
<tr><th colspan="4">Production Nozzle</th><th colspan="4" rowspan="2">Heating Up Nozzle</th></tr>
<tr><th colspan="4">Nozzles V = 25, 60 & 90°</th></tr>
<tr><th colspan="2">Oil Flow</th><th rowspan="2">Nozzle/ Needle
Ø /d in mm</th><th rowspan="2">Moveable Spreader Part</th><th rowspan="2">Oil Flow
Kg/h</th><th colspan="3">Nozzles V = 60 & 90°</th></tr>
<tr><th>Norminal Kg/h</th><th>Max/min Kg/h</th><th>Nozzle size in mm</th><th>Needle Size in mm</th><th>Movable Spreader Part</th></tr>
<tr><td colspan="8">Burner Ø 65mm</td></tr>
<tr><td>500</td><td>390-1400</td><td>3,0 / 1,5</td><td rowspan="9">$d_1 – D_1$
20 – 28
b = 4</td><td rowspan="9">200 – 800</td><td rowspan="9">Ø 2,4
V = 60°</td><td rowspan="9">d 1,0</td><td rowspan="9">$d_1 – D_1$
16 – 22
mm
b = 3</td></tr>
<tr><td>750</td><td>460-1650</td><td>3,5 / 1,5</td></tr>
<tr><td>1000</td><td>525-2000</td><td>4,0 / 2,0</td></tr>
<tr><td>1250</td><td>590-2300</td><td>4,5 / 2,5</td></tr>
<tr><td>1500</td><td>655-2600</td><td>5,0 / 3,0</td></tr>
<tr><td>1750</td><td>720-3000</td><td>5,5 / 3,5</td></tr>
<tr><td>2000</td><td>780-3300</td><td>6,0 / 4,0</td></tr>
<tr><td>2250</td><td>850-3600</td><td>6,5 / 4,5</td></tr>
<tr><td>2500</td><td>915-3900</td><td>7,0 / 5,0</td></tr>
<tr><td>2750</td><td rowspan="2">1000-4600</td><td rowspan="2">8,0 / 6,0</td><td rowspan="8">$d_1 – D_1$
24 – 34
b = 5</td><td rowspan="8">500 –2000</td><td rowspan="4">Ø 4,0
V = 90°</td><td rowspan="4">d 2,0</td><td rowspan="4">$d_1 = D_1$
20 / 28
b = 4</td></tr>
<tr><td>2950</td></tr>
<tr><td>3000</td><td rowspan="2">1200-5300</td><td rowspan="2">9,0 / 7,0</td></tr>
<tr><td>3250</td></tr>
<tr><td>3500</td><td rowspan="2">1300-7000</td><td rowspan="2">10,0 / 7,5</td><td rowspan="4">Ø 4,0
V = 60°</td><td rowspan="4">d 1,0</td><td rowspan="4">$d_1 = D_1$
16 – 22
b = 4</td></tr>
<tr><td>4000</td></tr>
<tr><td>4500</td><td rowspan="2">1400-9300</td><td rowspan="2">11,0 / 8,0</td></tr>
<tr><td>5000</td></tr>
<tr><td colspan="8">Burner Ø 85mm</td></tr>
<tr><td>5500</td><td rowspan="2">1600-10300</td><td rowspan="2">12,0 / 9,0</td><td rowspan="4">$d_1 – D_1$
28 – 40
b = 6</td><td rowspan="6">500 - 2000</td><td rowspan="6">Ø 4,0
V = 90°</td><td rowspan="6">d 2,0</td><td rowspan="14">$d_1 = D_1$
20 – 28
b = 4</td></tr>
<tr><td>6000</td></tr>
<tr><td>6500</td><td rowspan="2">1700-11300</td><td rowspan="2">13,0 / 10,0</td></tr>
<tr><td>7000</td></tr>
<tr><td>7500</td><td rowspan="2">1850-15700</td><td rowspan="2">14,0 / 10,0</td><td rowspan="8">$d_1 – D_1$
28 – 40
b = 9</td></tr>
<tr><td>9000</td></tr>
<tr><td>9000</td><td rowspan="2">2100-18400</td><td rowspan="2">16,0 / 12,0</td><td rowspan="8">800 – 3300</td><td rowspan="8">Ø 6,0
V = 60°</td><td rowspan="8">d 4,0</td></tr>
<tr><td>12000</td></tr>
<tr><td>12000</td><td rowspan="2">2300-21000</td><td rowspan="2">18,0 / 14,0</td></tr>
<tr><td>15000</td></tr>
<tr><td>15000</td><td rowspan="2">2750-24000</td><td rowspan="2">20 / 16,0</td><td rowspan="2">32 – 46
b = 10</td></tr>
<tr><td>18000</td></tr>
</table>



D1
d1
b
V = 60 o or 90o
Ø
b
V = 25 o
Ø
Bronze Speader
b
d

General:

The burner set OBA is used for injecting and atomising liquid fuels. Compressed air at an inlet pressure of 5-7 bar is used for atomisation. The primary applications are firing in rotary kilns and calciners. The burner set can be used for gas oil, fuel oil or secondary liquid fuels with viscosity's up to 300 cSt.

The standard range comprises burner sets for max. capacities up to 25000 kg/h

Features:

- **Uniform atomisation**
- **Low atomising air consumption**
- **Large turn-down ratio**
- **Simple, robust design, no moving parts**
- **Will accept fluids with solid particles up to 5-6 mm**
- **Can be supplied for chemically aggressive fluids**

Arrangement:

The OBA burner set will normally be placed in a protective tube at the central part of the burner. The burner set can be used in connection with all normal kiln burner types provided that there is sufficient space.

Fuel and atomising air are mixed in the mixing chamber before it is discharged through the nozzle openings. The nozzle openings can be sized allowing for solid particles with diameters of up to 5-6 mm. The spraying angle can be made to fit any requirement. For kiln burner applications it will normally be 45-60 °.

For gas oil, heavy fuel oil or secondary fuels with a max. viscosity of 17 cSt the atomising air consumption will normally be in the range of 5-6 % (mass) of the liquid fuel capacity. For fuels with a higher viscosity the atomising air consumption may be increased -up to 12-15 % of max. fuel capacity- depending on the viscosity.

Burner set type OBA-DF

The OBA – DF is designed to operate with two different fuels simultaneously.
For example gas-oil, heavy fuel or other liquid fuels, on condition that the fuel is delivered at a pressure of minimum 6 bar. One of the fuels must have a viscosity of max.2,5^{o}E = 17 cSt. The second fuel can have a viscosity of up to 300 cSt.

In special occasion the viscosity can be high but in these cases the burner must be specially design .

Atomising Air

The standard requirement for atomising air is:

1 kg/ hr atomising air per mm^2 nozzle area

Adjustment of atomising air with and without a flowmeter.

Most OBA burner installations are delivered with a flow meter. In some cases when an OBA burner is delivered as a heating-up burner no flowmeter is installed.

Adjustment of atomising air with an installed flow meter.
The atomising air flow is found by using the table and curve included in the burner operation instructions for these specific nozzles and adjusting the constant flow valve accordingly.
(the curve in the instruction is made for the specific flow meter installed)

Example:

- A nozzle with 8 pcs. 5mm holes is used
- Compressed air pressure is 6 bar.
- Compressed air temp. 20^o C.

From the curve the following is found:
At 6 bar and 20 ^{o}C shows that the 100% scale equals 210 kg/h
(see curve page **J-8**)

The table indicates that a nozzle of this size needs 157 kg/h

Calculated : (1 kg/hr per mm^2)

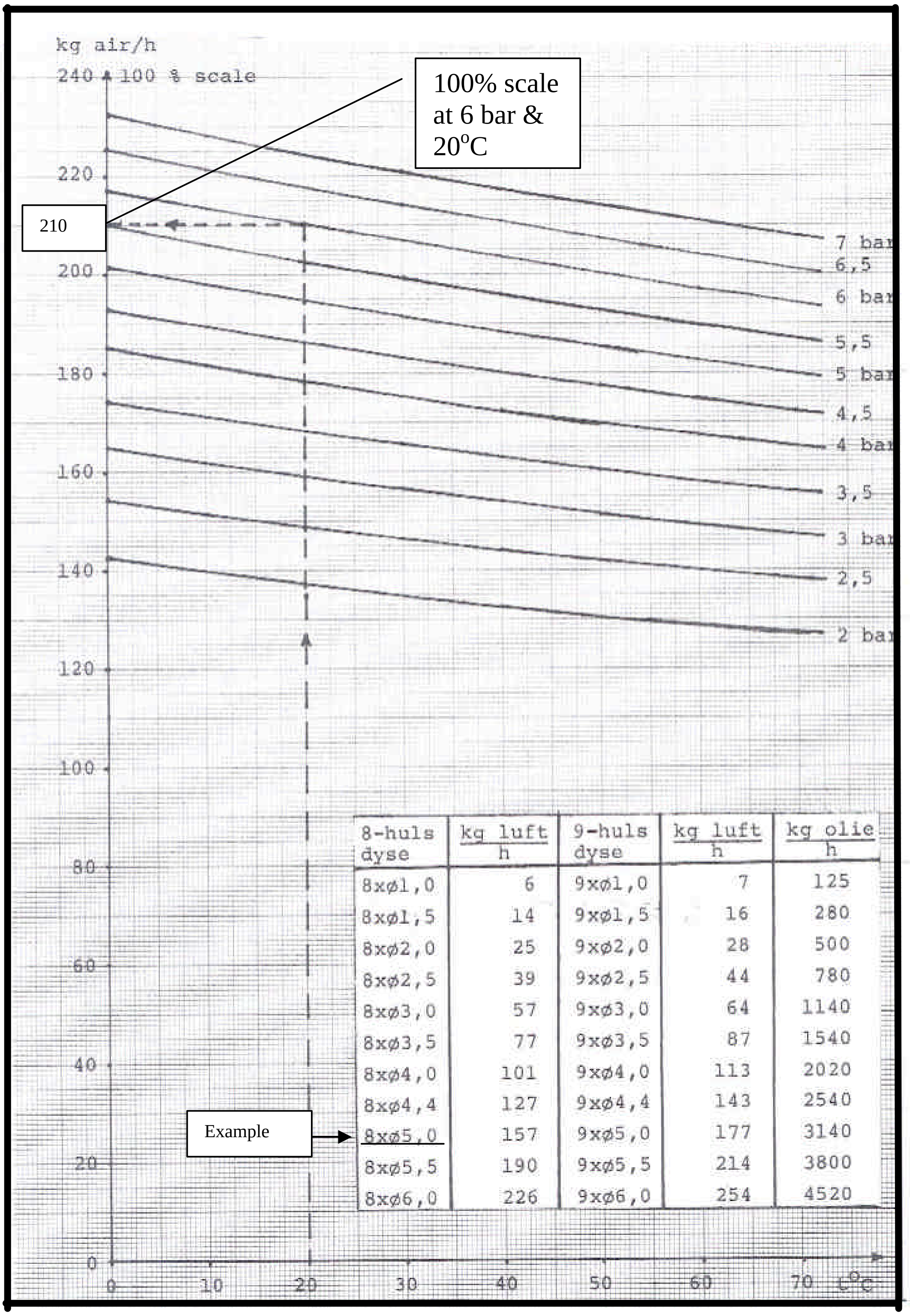
$$\pi r^2 \times \text{No holes} \times 1 = 3.142 \times 2{,}5^2 \times 8 \times 1 = 157{,}1\,\text{kg/hr}$$

The constant air flow valve should be adjusted until the flow meter indicates:

$$\frac{157}{210} \times 100\% = \underline{74{,}8\%}$$

Adjustment of atomising air without a flow meter.
When no flow meter is installed the atomising air adjusted by:

Adjusting the constant flow valve until you have an indication of 0,6 bar on the pressure gauge situated on the fuel inlet to the OBA burner .



8-huls dyse	kg luft / h	9-huls dyse	kg luft / h	kg olie / h
8xø1,0	6	9xø1,0	7	125
8xø1,5	14	9xø1,5	16	280
8xø2,0	25	9xø2,0	28	500
8xø2,5	39	9xø2,5	44	780
8xø3,0	57	9xø3,0	64	1140
8xø3,5	77	9xø3,5	87	1540
8xø4,0	101	9xø4,0	113	2020
8xø4,4	127	9xø4,4	143	2540
8xø5,0	157	9xø5,0	177	3140
8xø5,5	190	9xø5,5	214	3800
8xø6,0	226	9xø6,0	254	4520

Note: For calciner burners 2 hole nozzles are normally used.

Cooler Operating Standards

	Clinker Temp. °C Above amb.	Standard Heat Loss	Cooling Air	Power Consumption kWh/t		Rad. Loss
SF-cooler	65	95 kcal/kg cl VDZ basis ref. amb.	2,3 kg/ kg cl	Cooling Air Fans (Fix speed)	4,4	4 kcal/kg
				Cooling Air Fans (Var. Speed)	4,0	
				Excess Air (Var. speed)	0,75	
				Grate Drives	0,65	
				Hammer Crusher	0,15	
				Hyd. Roller Break.	0,3	
	80	95 kcal/kg cl VDZ basis ref. amb.	2,15 kg/kg cl	Cooling Air Fans (Fix speed)	4,1	
				Cool. Fans (Var. Speed)	3,7	
				Excess Air (Var. speed)	0,65	
				Grate Drives	0,65	
				Hammer Crusher	0,15	
				Hyd. Roller Break.	0,3	
	Clinker Temp. °C	**Standard Heat Loss**	**Cooling Air**	**Power Consumption**		
COOLAX cooler	65	110 kcal/kg cl VDZ basis ref. amb.	2,55 kg/ kg cl	Cooling Air Fans (Fix speed)	5,1	4 kcal/kg
				Excess Air Fan (Var. Speed)	0,6	
				Grate Drives (Mech.)	0,12	
				Grate Drives (Hyd.)	0,4	
				Hammer Crusher	0,15	
				Hyd. Roller Break.	0,3	
	80	110 kcal/kg cl VDZ basis ref. amb.	2,35 kg/kg cl	Cooling Air Fans (Fix speed)	4,7	
				Excess Air Fan (Var. Speed)	0,65	
				Grate Drives (Mech.)	0,12	
				Grate Drives (Hyd.)	0,4	
				Hammer Crusher	0,15	
				Hyd. Roller Break.	0,3	

A) TOTAL COOLER LOSS
Reference temperature = 0 °C
CL_T = Q in Clinker from Cooler
+ Q in Excess air
+ Q in Hot Air
+ Radiation

B) VDZ COOLER LOSS (also known as NET Cooler Loss)
Reference Temperature = Cooling Air Temperature
CL_{VDZ} = Q (Clinker from Cooler) – Q (Clinker at Cooling Air Temperature)
+ Q (Excess Air) – Q (excess Air at Cooling Ait Temperature)
+ Q (Hot Air) – Q (Hot Air at Cooling Air Temperature)
+ Radiation

C) STANDARD COOLER LOSS
Cooler Loss independent of Kiln System
Normalise:
- Combustion Air Requirement = 1,15 kg/kg cl
- Cooling Air Temperature = 18 °C

	Units	Unax	Rotary	Folax Con.Grate	Coolax Beam	SF Cooler Cross Bar
Cooling Air	kg/kg cl	Combust. Air	Combust. Air	2,95	2,35	2,15
Radiation	kcal/kcal	95	75	6	4	4
Excess Air	^{o}C	0	0	108	280	280
Clinker Temp.	^{o}C	150	225	90	80	80
Standard Cooler loss	kcal/kg	140	130	130	110	90
Power Consumption	kWh/ton	1,5 (Common Drive)	3,5	4,7	5,90	5,55

Power Consumption Folax, Coolax and SF – Cooler include: Cooling Air fans (w. Fix speed), Excess Air Fan (w. Variable speed), Hydraulic grate drives, and Hammer Crusher.

Cooler Tube load based on tube shell temperatures:

- Measure shell temp. the length of each tube every 1 meter.
- Calculate avg. temp. for each tube.
- Sum temperatures of avg.temperture for all the tubes.

Calculation:

$$\text{Normal Load in \%} = \frac{\mathbf{100}}{\mathbf{No.\ of\ Tubes}}\ \%$$

$$\text{Percent load per tube} = \frac{\mathbf{Average\ shell\ temp.of\ specific\ tube}}{\mathbf{Sum\ of\ average\ temperatures\ of\ all\ tubes}}\ \%$$

$$\text{Actual Load of each tube} = \frac{\mathbf{Percent\ load\ per\ tube}}{\mathbf{Normal\ load}}\ \%$$

Cooler Tube load based clinker temperatures from each tube :

- Measure clinker temp from each tube.
- Calculated avg. clinker temp. from each tube
- Sum average clinker temperatures from all tubes.

$$\text{Total Average clinker temperature} = \frac{\mathbf{Sum\ of\ average\ clinker\ tempratures}}{\mathbf{No.\ of\ tubes}}$$

$$\text{Load based on clinker temp.} = \frac{\mathbf{Avg.\ clinker\ temp.\ of\ tube}}{\mathbf{Total\ average\ clinker\ temp}}\ \%$$

Load based on shell temperature				**Load based on clinker temperature**		
Normal Load per tube		11,11	%			
Tube No.	Avg Shell Temp. ^oC	Load per tube %	Actual Load %	Tube No.	Avg.Cl. Temp. ^oC	Actual Load %
1	287	11,13	100	1	164	119
2	260	10,11	91	2	98,4	71
3	364	14,11	127	3	278,4	201
4	261	10,12	91	4	66,6	48
5	350	13,59	122	5	279,6	202
6	258	10,02	90	6	76,3	55
7	309	11,98	108	7	151,7	110
8	189	7,32	66	8	43,8	32
9	299	11,62	105	9	86,6	63
Sum	2577	100				

The load calculate by the clinker temperature will give a more accurate load indication due to the fact that a higher shell temp. would mean a higher temperature difference between clinker and shell. Load according to shell temp. can be used when it is not possible to measure the clinker temperature

Refractory Codes

Group	Material Designation
BA	Basic bricks
HAL	High-Alumina
CH	Fire Bricks
IF	Refractory cement
W	Insulating lining bricks
IA-IL-IW	Insulating materials
HY	Hydraulic castables
GU	Gunning masses
PR	Phosphate-bonded ramming masses

Glossary:

Density (kg/m^3)	The density of refractory is an indirect measure of their heat capacity or ability to store heat
Porosity (%)	The porosity of a refractory has an effect upon its ability to resist penetration by metals, slag and fluxes, in general the higher the porosity, the greater the effect of the refractory
Crushing strength (N/mm^2)	The compressive load required to crush a refractory.
Basic refractory	Refractory which consist essentially of magnesia, lime, chrome ore or mixtures of two or more of these and when heated, can react chemically with acid refractory, slag and fluxes
Spinel	1. The mineral composed of magnesium aluminate; $MgAl_2O_4$. Specific gravity 3,6. Melting point 2135 ^oC. 2. A group of minerals of general formula; AB_2O_4 where A represents magnesium, ferrous iron, zinc or manganese, ferric iron or chromium.
Fire bricks	Refractory brick of any type
High-Alumina Refractory	Alumina-silica refractory containing 45 or more alumina. The materials used in their production include diasporas, bauxite, gibbsite, kyanite, sillimanite, andalusite and fuse alumina (artificial corundum)
Castable Refractory	A mixture of heat-resistant aggregate and a heat-resistant hydraulic cements; for use, is mixed with water and rammed, cast or gunned into place.
Monolithic Lining	A lining without joints, formed of material which is rammed, cast gunned or sintered into place
Gunning	the application of monolithic refractory by means of air-placement guns.
Mortar (Refractory)	A finely ground refractory material which becomes plastic when mixed with water and is suitable for use in laying refractory.

Codes and guideline data.

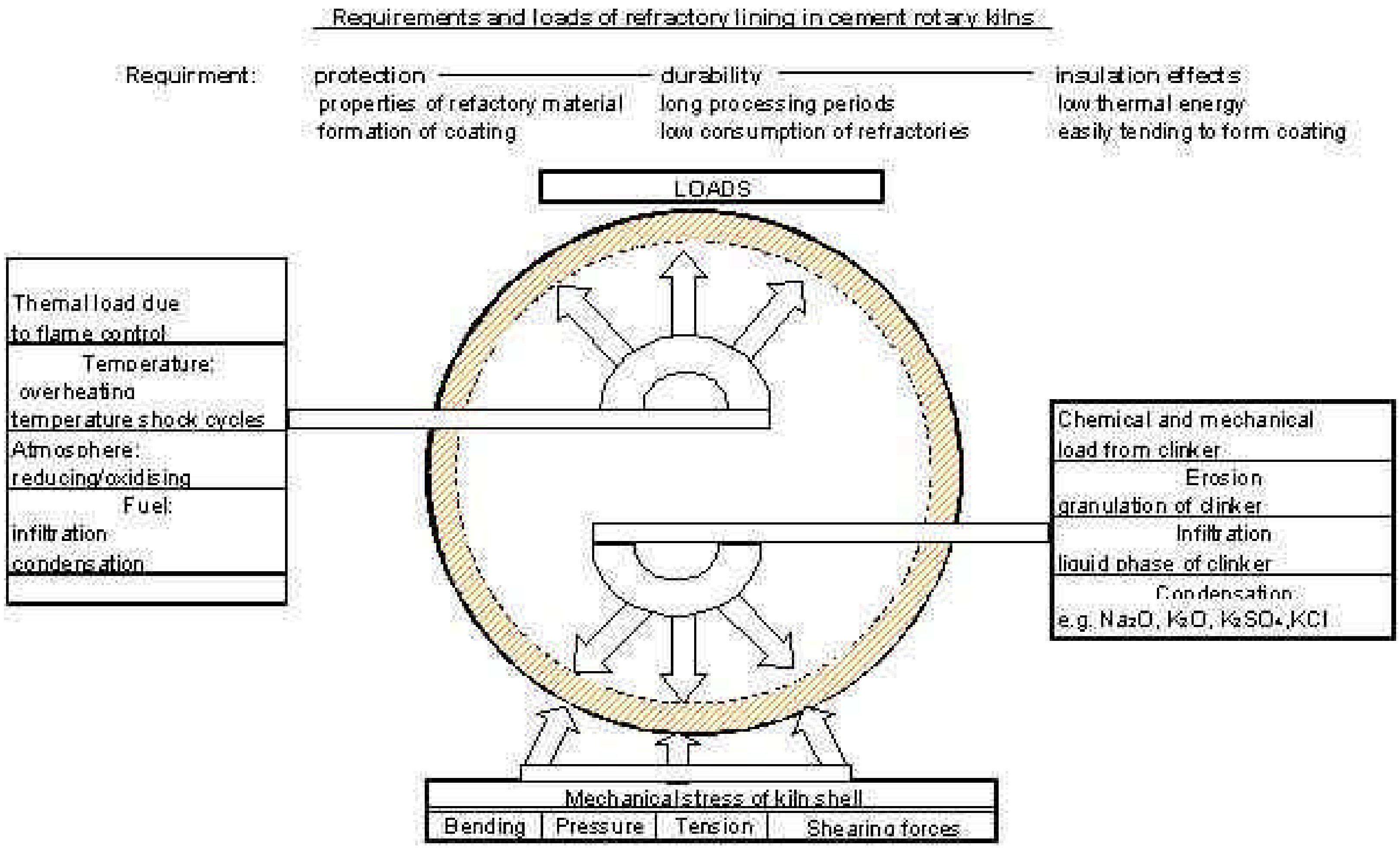
Bricks and Castable.

Codes	Al_2O_3	Cold Crushing Strength	Porosity	Thermal Shock Resistance	Max. service Temperature
	%	N/mm^2	%	Cycles	^oC
Fire Bricks					
CH-3	40	>40	<19	20	1400
CH-4	35-40	>35	<20	15	1350
CH-6	30-35	>35	<22	15	1350
CH-7	25-30	>65	<14	15	1250
High -Alumina Bricks					
HAL-1	85	80	18-20	30	1500
HAL-2	75	>70	18-20	30	1500
HAL-5	63	>50	14-16	50	1600
Insulating Lining Bricks					
W-8	-	>20	-	-	1350
W-9	-	>2,5	-	-	900
W-10	-	>10	-	-	950
W-11	-	>18	-	-	1000
Hydraulic castables					
HY-1	90	100	-	-	1800
HY-3	45	40	-	-	1400
HY-4	40	25	-	-	1300
HY-5	35	20	-	-	1250
HY-8	50	80	-	-	1500
HY-9	22	45	-	-	1150
HY-10	35	12	-	-	1300
HY-11	60	80	-	-	1600
HY-14	40	20	-	-	1600
HY-16	55	30	-	-	1500
HY-18	80	100	-	-	1650
HY-19	40-50	15	-	-	1300

Burning Zone Bricks

Codes	MgO	Al_2O_3	Cr_2O_3	Cold crushing strength	Thermal shock resistance
Basic Bricks					
BA-3	60-75	12	7-11	30	30
BA-4	70-85	2-6	5-10	35	30
BA-9	90-93	5-7	0	50	40
BA-10	85-89	9-12	0	50	40

(Note: Due to environmental reasons bricks with chrom content are rarely used)


Requirements and loads of refractory lining in cement rotary kilns
Requirment:
protection
properties of refactory material
formation of coating
durability
long processing periods
low consumption of refractories
insulation effects
low thermal energy
easily tending to form coating
LOADS
Themal load due to flame control
Temperature:
overheating
temperature shock cycles
Atmosphere:
reducing/oxidising
Fuel:
infiltration
condensation
Chemical and mechanical load from clinker
Erosion
granulation of clinker
Infiltration
liquid phase of clinker
Condensation
e.g. Na2O, K2O, K2SO4,KCl
Mechanical stress of kiln shell
Bending
Pressure
Tension
Shearing forces

Kiln Preheat

Drying Out Of refractory:

The initial drying out rate should be 72 hrs. During the initial preheat the rate of heating should not exceed 25 ^{o}C /hr. for the top stage cyclone temperature. This is to allow for thermal equilibrium between the brick work and kiln shell. if the temperature is raised to quickly, thermal stress may cause spalling of the brick.

The following is recommended barring schedule for the first preheat:

00 – 08 hours........................Turn the kiln 200^{o} every 30 minutes
24 – 68 hours........................Turn the kiln 200^{o} every 15 minutes
68 – 72 hours........................Turn the kiln Continuously on the auxiliary drive

(NB!! If it rains the kiln must be turned continuously)

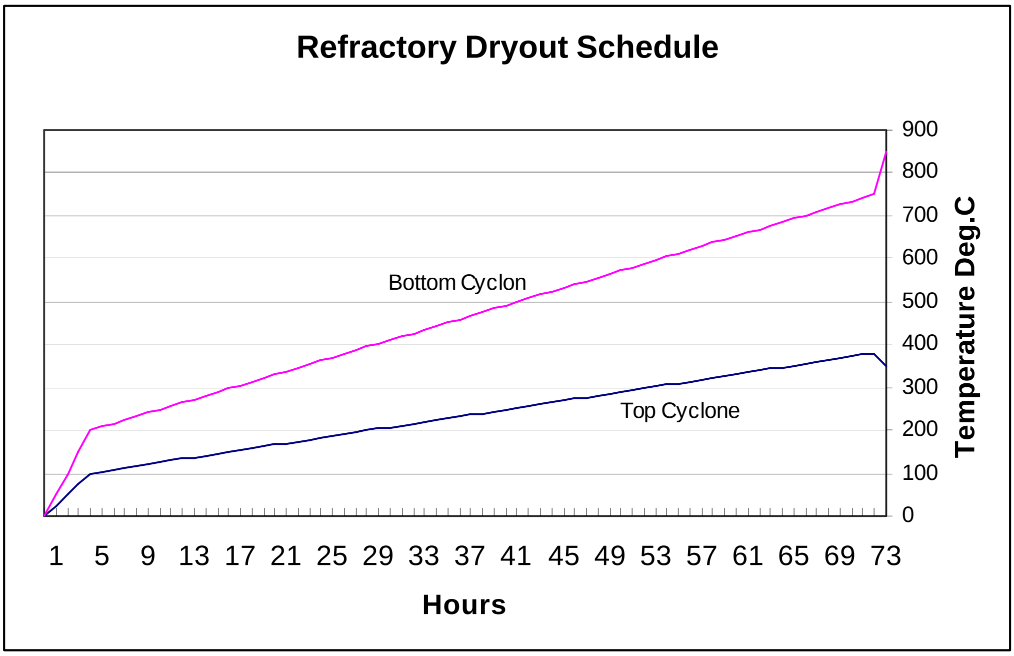
Normal 24 hr. Preheat barring schedule after maintenance shutdown
00 – 08 hours.........................Turn the kiln 200^{o} every 30 minutes
08 – 20 hours.........................Turn the kiln 200^{o} every 15 minutes
20 – 24 hours.........................Turn the kiln Continuously on the auxiliary drive

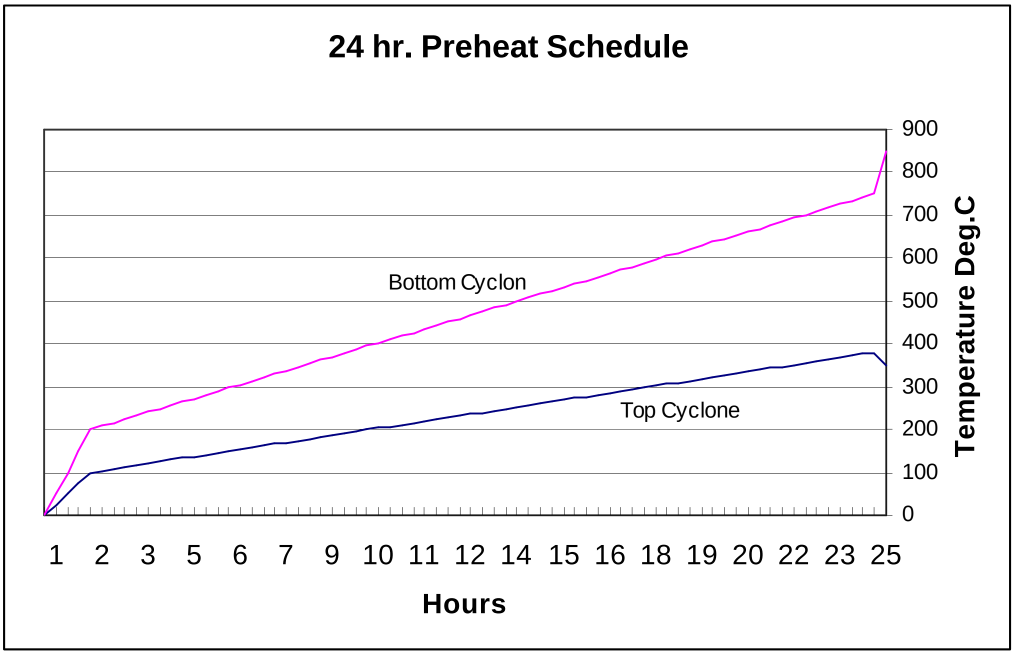
(NB!! If it rains the kiln must be turned continuously)

As it is the standard to turn the Rotax kiln 200^{o} during the barring program 200^{o} has been inserted into these barring schedules.

Lining Temperature vs. Brick Colour

Temp. ^{o}C	Brick Colour
500	Dark Red (just visible)
600	Dark Red
700	Dark Red to Cherry Red
800	Cherry Red
900	Cherry Red to Bright Cherry Red
1000	Orange Red
1100	Bright Orange to Yellow
1200	Bright Yellow
1300	Bright Yellow to White
1400	White
1500	White to Brilliant White
1600	Brilliant White till To Late





Cooling Down Barring Schedule

Hour 0 - ½ ....Continuous barring
Hour ½ - 24 ....Turn the kiln 200^{o} every 15 minutes
Hour 24-48 ....Turn the kiln 200^{o} every 30 minutes
Hour 48 - ....bar as required

(NB!! If it rains the kiln must be turned continuously)

Standard False Air in Kiln Systems

Input Field	Units	Standard Values SP	ILC-E	ILC	ILC-D	SLC-S	SLC	Remarks
False Air with Feed	kg/kg cl	0,10						Airlift
		0,04						Screwpump
		0,00						Elevator
False Air Kiln hood	kg/kg cl.			0,03				
False Air Inlet seal	kg/kg cl.	0,07	0,07	0,03	0,03	0,03	0,03	
False air K1	kg/kg cl			0,03			0,015	
False air K2				0,02			0,005	
False air K3				0,02			0,005	
False air K4				0,02			0,005	
False air K5				0,02			0,005	
False air K6				0,02			0,005	
False air C1	kg/kg cl						0,025	
False air C2							0,015	
False air C3							0,015	
False air C4							0,015	
False air C5							0,015	
False air C6							0,015	
False air Calciner	kg/kg cl.		0,01					
Primary Air ,Kiln	kg/kg cl	0,15						Coal Firing
		0,10						Oil/Gas Firing
Primary Air, Calciner	kg/kg cl		0,05					Coal Firing
								Oil firing
			0					Gas
% feed to C-string	%						~ 60	
LOI (%) Kiln string to Calciner	%	20					17	
LOI (%) to Kiln								
LOI (%) Calciner to Kiln			16	5	5	5	5	

Assumed surface loss from Preheater with lining in good condition

	SP	ILC-E	ILC	SLC-S	SLC-D	SLC-I	SLC	No, of Stages
Surface Loss K1 [kcal/kg]	3,0	3,0	3,0	3,0	3,0	1,7	1,7	4
	2,8	2,8	2,8	2,8	2,8	1,5	1,5	5
	2,5	2,5	2,5	2,5	2,5	1,3	1,3	6
Surface Loss K2 [kcal/kg]	3,0	3,0	3,0	3,0	3,0	1,6	1,6	4
	3,0	3,0	3,0	3,0	3,0	1,5	1,5	5
	2,5	2,5	2,5	2,5	2,5	1,4	1,4	6
Surface Loss K3 [kcal/kg]	4,7	5,3	5,3	5,3	5,3	2,3	2,3	4
	3,0	3,6	3,6	3,6	3,6	1,9	1,9	5
	2,5	3,0	3,0	3,0	3,0	1,5	1,5	6
Surface Loss K4 [kcal/kg]	8,0	10,0	16,0	18,0	18	8	4,5	4
	4,6	6,0	6,0	6,0	6	3	3	5
	3,5	4,8	4,8	4,8	4,8	2,5	2,5	6
Surface Loss K5 [kcal/kg]	8,0	10,0	16,0	18,0	18	8	4,5	5
	5,2	6,0	6,0	6,0	6	3,5	3,5	6
Surface Loss K6 [kcal/kg]	8,0	10,0	16,0	18,0	18	8	4,5	6
Surface Loss C1 [kcal/kg]							2,6	4
							2,3	5
							2,1	6
Surface Loss C2 [kcal/kg]							2,8	4
							2,3	5
							2,0	6
Surface Loss C3 [kcal/kg]							4,0	4
							2,7	5
							2,3	6
Surface Loss C4 [kcal/kg]							9,5	4
							4,5	5
							4,0	6
Surface Loss C5 [kcal/kg]							9,5	5
							4,7	6
Surface Loss C6. [kcal/kg]							9,5	6

**) Heat loss from Calciner, tertiary air duct and riser pipe is included in the last stage surface loss (C-string for SLC)*

Element	Symbol	Atom No.	Atomic Weight	Element	Symbol	Atom No.	Atomic Weight
Actinium	Ac	89	227,028	**Mercury**	**Hg**	**80**	**200,59**
Aluminium	**Al**	**13**	**26,9815**	Molybdenum	Mo	42	95,94
Americium	Am	95	243	Neodymium	Nd	60	144,24
Antimony	Sb	51	121,750	Neon	Ne	10	20,183
Argon	Ar	18	39,9480	Neptunium	Np	93	237
Arsenic	As	33	74,9216	Nickel	Ni	28	58,71
Astatine	At	85	210	Niobium	Nb	41	92,906
Barium	Ba	56	137,34	**Nitrogen**	**N**	**7**	**14,0067**
Berkelium	Bk	97	247	Nobelium	No	102	259
Beryllium	Be	4	9,0122	Osmium	Os	76	190,20
Bismuth	Bi	83	208,98	**Oxygen**	**O**	**8**	**15,9994**
Boron	B	5	10,811	Palladium	Pd	46	106,40
Bromine	Br	35	79,909	Phosphorus	P	15	30,9738
Cadmium	Cd	48	112,40	Platinum	Pt	78	195,09
Cesium	Cs	55	132,905	Plutonium	Pu	94	242
Calcium	**Ca**	**20**	**40,08**	Polonium	Po	84	209
Californium	Cf	98	251	**Potassium**	**K**	**19**	**39,102**
Carbon	**C**	**6**	**12,011**	Praseodymium	Pr	59	140,907
Cerium	Ce	58	140,12	Promethium	Pm	61	145
Chlorine	**Cl**	**17**	**35,453**	Protactinium	Pa	91	231
Chromium	Cr	24	51,996	Radium	Ra	88	266
Cobalt	Co	27	58,933	Radon	Rn	86	222
Copper	Cu	29	63,54	Rhenium	Re	75	186,2
Curium	Cm	96	247	Rhodium	Rh	45	102,905
Dysprosium	Dy	66	162,50	Rubidium	Rb	37	85,47
Einsteinium	Es	99	252	Ruthenium	Ru	44	101,07
Erbium	Er	68	167,26	Samarium	Sm	62	150,35
Europium	Eu	63	151,96	Scandium	Sc	21	44,956
Fermium	Fm	100	257	Selenium	Se	34	78,96
Fluorine	F	9	18,998	**Silicon**	**Si**	**14**	**28,086**
Francium	Fr	87	223	Silver	Ag	47	107,870
Gadolinium	Gd	64	157,25	**Sodium**	**Na**	**11**	**22,9898**
Gallium	Ga	31	69,720	Strontium	Sr	38	87,62
Germanium	Ge	32	72,590	**Sulphur**	**S**	**16**	**32,064**
Gold	Au	79	196,967	Tantalum	Ta	73	180,948
Hafnium	Hf	72	178,49	Technetium	Tc	43	98,9
Helium	He	2	4,0026	Tellurium	Te	52	127,6
Holmium	Ho	67	164,93	Terbium	Tb	65	158,924
Hydrogen	**H**	**1**	**1,00797**	Thallium	Tl	81	204,37
Indium	In	49	114,82	Thorium	Th	90	232,038
Iodine	I	53	126,90	Thulium	Tm	69	168,93
Iridium	Ir	77	192,20	Tin	Sn	50	118,69
Iron	**Fe**	**26**	**55,847**	Titanium	Ti	22	47,90
Krypton	Kr	36	83,80	Tungsten	W	74	183,85
Lanthanum	La	57	138,91	Uranium	U	92	238,03
Lawrencium	Lw	103	262	Vanadium	V	23	50,942
Lead	Pb	82	207,10	Xenon	Xe	54	131,30
Lithium	Li	3	6,939	Ytterbium	Yb	70	173,04
Lutetium	Lu	71	174,97	Yttrium	Y	39	88,905
Magnesium	**Mg**	**12**	**24,312**	Zinc	Zn	30	65,37
Manganese	Mn	25	54,938	Zirconium	Zr	40	91,22
Mendelevium	Md	101	258				

**** Based on the atomic mass of the (^{12}C) isotope = 12.0000***

Specific Heat

Temperature	kcal/kg. °C							
°C	Air	O_2	N_2	CO_2	CO	H_2	Steam	SO_2
0	0,24	0,218	0,248	0,196	0,248	3,403	0,443	0,145
50	0,240	0,219	0,248	0,202	0,248	3,418	0,444	0,146
100	0,240	0,22	0,249	0,208	0,249	3,433	0,446	0,152
150	0,241	0,221	0,249	0,213	0,249	3,44	0,448	0,155
200	0,241	0,223	0,25	0,219	0,25	3,448	0,451	0,158
250	0,242	0,225	0,25	0,224	0,251	3,543	0,453	0,161
300	0,243	0,227	0,251	0,229	0,252	3,458	0,456	0,164
350	0,244	0,229	0,252	0,232	0,253	3,460	0,459	0,166
400	0,245	0,231	0,253	0,236	0,254	3,463	0,463	0,169
450	0,246	0,232	0,254	0,240	0,255	3,465	0,466	0,171
500	0,247	0,234	0,255	0,244	0,257	3,468	0,47	0,173
600	0,249	0,237	0,257	0,251	0,260	3,478	0,477	0,177
700	0,251	0,240	0,259	0,256	0,262	3,488	0,485	0,18
800	0,253	0,243	0,262	0,261	0,265	3,503	0,493	0,183
900	0,256	0,245	0,265	0,266	0,268	3,518	0,502	0,185
1000	0,259	0,248	0,267	0,270	0,27	3,532	0,509	0,187
1100	0,261	0,249	0,270	0,274	0,273	3,547	0,517	0,189
1200	0,263	0,251	0,272	0,277	0,275	3,572	0,524	0,191
1300	0,265	0,253	0,274	0,28	0,277	3,592	0,532	0,192
1400	0,267	0,255	0,276	0,283	0,279	3,612	0,539	0,194
1500	0,269	0,256	0,278	0,285	0,280	3,632	0,546	0,195
1600	0,271	0,258	0,279	0,288	0,282	3,652	0,553	0,196
1700	0,272	0,259	0,281	0,290	0,283	3,671	0,56	0,197
1800	0,273	0,26	0,282	0,292	0,285	3,696	0,566	0,198
1900	0,275	0,262	0,283	0,294	0,286	3,716	0,572	0,198
2000	0,276	0,263	0,285	0,295	0,287	3,736	0,578	0,199
2100	0,277	0,264	0,286	0,297	0,289	3,756	0,584	0,200
2200	0,278	0,265	0,287	0,298	0,29	3,781	0,589	0,201
2300	0,28	0,266	0,288	0,300	0,291	3,800	0,594	0,201
2400	0,281	0,267	0,289	0,301	0,292	3,820	0,599	0,202
2500	0,282	0,268	0,29	0,302	0,293	3,840	0,603	0,202
2600	0,283	0,269	0,291	0,303	0,294	3,860	0,608	0,203
2700	0,284	0,270	0,292	0,304	0,295	3,875	0,612	0,203
2800	0,285	0,271	0,293	0,305	0,296	3,895	0,617	0,204
2900	0,286	0,273	0,294	0,306	0,297	3,140	0,62	0,204
3000	0,287	0,274	0,295	0,307	0,298	3,929	0,623	0,204

Heat content of, Steam, CO_2 , Rawmeal, Dust & Clinker kcal/kg

Temperature	Heat Content kcal/kg					
°C	Air	Steam	CO2	Rawmeal	Dust	Clinker
5	1	596,6		1		
10	2	599,0		2		
15	3	601,4		3		
20	4	603,7		4		
25	6	606,1		5		
30	7	608,4	6	6	6	5
35	8	610,7	7	7	7	6
40	10	613,0	8	8	8	7
45	11	615,3	9	9	9	8
50	12	617,6	10	10	10	9
55	13	619,9	11	12	11	10
60	14	622,2	12	13	12	11
65	16	624,4	13	14	13	12
70	17	626,6	14	15	14	13
75	18	628,8	15	16	15	14
80	19	630,9	16	17	16	15
85	20	633,1	18	18	17	16
90	21	635,2	19	19	18	17
95	23	637,3	20	20	19	18
100	24	639,1	21	21	20	19
105	25	641,7	22	22	21	20
110	26	644,2	23	24	23	21
115	28	646,7	24	25	24	22
120	29	649,1	25	26	25	23
125	30	651,5	26	27	26	24
130	31	653,8	28	28	27	25
135	32	656,2	29	30	29	26
140	34	658,5	30	31	30	27
145	35	660,9	31	32	31	28
150	36	663,2	32	33	32	29
155	37	665,6	33	34	33	30
160	38	667,9	34	36	34	31
165	40	670,2	36	37	35	32
170	41	672,5	37	38	37	34
175	42	674,9	38	39	38	35
180	43	677,2	39	40	39	36
185	44	679,5	40	42	40	37
190	46	681,8	42	43	41	38
195	47	684,2	43	44	42	39
200	48	686,5	44	45	43	40
205	50	688,8	45	46	44	41
210	51	691,1	46	47	45	42
215	52	693,5	47	48	46	43
220	53	695,8	48	50	48	44
225	54	698,2	50	51	49	45

Heat content of, Steam, CO_2 , Rawmeal, Dust & Clinker kcal/kg

Temperature °C	Air	Steam	CO2	Rawmeal	Dust	Clinker
	Heat Content kcal/kg					
230	56	700,5	51	52	50	46
235	57	702,9	52	53	51	48
240	58	705,2	53	54	52	49
245	60	707,6	55	56	54	50
250	61	709,9	56	57	55	51
255	62	712,3	57	58	56	52
260	63	714,6	58	60	58	53
265	64	717	60	61	59	54
270	66	719,3	61	62	60	55
275	67	721,7	62	63	61	56
280	68	724	63	64	62	57
285	70	726,4	65	66	64	59
290	71	728,8	66	67	65	60
295	72	731,2	67	68	66	61
300	73	733,5	69	69	67	62
305	74	735,9	70	70	68	63
310	76	738,3	71	72	69	64
315	77	740,7	72	73	70	66
320	78	743,1	74	75	72	67
325	80	745,5	75	76	73	68
330	81	747,9	76	78	75	69
335	82	750,3	78	79	76	70
340	83	752,7	79	80	77	72
345	84	755,1	80	82	78	73
350	86	757,5	81	83	80	74
355	87	759,9	82	84	81	75
360	88	762,3	84	85	82	76
365	90	764,8	85	86	83	78
370	91	767,2	87	87	84	79
375	92	769,7	88	89	86	80
380	93	772,1	89	91	88	81
385	94	774,6	90	92	89	82
390	96	777,0	92	93	90	83
395	97	779,5	93	95	91	84
400	98	781,9	94	96	93	86
405	100	784,4	96	98	94	87
410	101	786,8	97	99	95	88
415	102	789,3	98	100	96	89
420	103	791,8	100	102	98	90
425	104	794,3	101	103	99	92
430	106	796,7	102	104	100	93
435	107	799,2	104	106	102	94
440	108	801,7	105	107	103	95
445	110	804,2	107	108	104	96
450	111	806,7	108	110	106	98

Heat content of, Steam, CO_2 , Rawmeal, Dust & Clinker kcal/kg

Temperature	Heat Content kcal/kg					
°C	Air	Steam	CO2	Rawmeal	Dust	Clinker
455	112	809,3	110	111	107	99
460	114	811,8	111	113	109	100
465	115	814,3	112	114	110	101
470	116	816,8	114	116	111	102
475	118	819,4	115	117	113	104
480	119	821,9	116	118	114	105
485	120	824,9	118	120	115	106
490	122	827	119	121	116	108
495	123	829,6	120	122	117	109
500	124	832,1	122	124	119	110
505	125	834,7	124	125	121	112
510	127	837,3	125	127	122	113
515	128	839,9	126	128	123	114
520	129	842,5	128	130	125	115
525	130	845,1	129	131	126	116
530	132	847,7	130	132	127	118
535	133	850,3	132	134	129	119
540	134	852,9	133	135	130	120
545	135	855,5	135	136	131	122
550	137	858,1	136	138	133	123
555	138	860,7	138	139	134	124
560	140	862,9	140	141	136	125
565	141	865,7	141	142	137	127
570	142	866,1	142	144	139	128
575	144	868,7	144	145	140	129
580	145	871,2	145	146	141	130
585	146	874,8	146	148	142	131
590	148	878	148	149	143	132
595	149	880,9	149	150	144	134
600	151	883,7	151	152	146	135
605	152	886,6	152	153	147	136
610	154	889,1	154	155	149	138
615	155	892	155	156	150	139
620	156	894,8	157	158	152	141
625	158	897,9	158	159	153	143
630	159	902,1	160	161	155	144
635	160	905,8	161	163	157	146
640	162	909	163	164	159	147
645	163	912,1	164	165	160	149
650	164	914,3	165	166	161	150
655	166	916,5	167	168	163	152
660	167	918,7	168	169	164	153
665	168	920,8	170	171	166	154
670	170	922,9	171	172	167	155
675	171	925,2	172	174	169	156
680	172	927,3	174	175	170	157
685	174	929,5	175	177	172	158
690	175	931,8	176	178	173	159
695	176	934,2	177	179	174	160
700	177	936,7	179	181	176	161

Density

1 t/m^3	= 62,4	lb/ft^3			
SI 1 kg/m^3	= 1,686	lb/yd^3	1 lb/yd^3	= 0,593	kg/m^3
SI 1 kg/m^3	= 0,0624	lb/ft^3	1 lb/ft^3	= 16,02	kg/m^3
1 g/m^3	= 0,437	gr/ft^3 *(grain/ft³)*			
1 g/m^3	= 0,0702	gr/ft^3			

Pressure

SI 1Pa (Pascal)	= 1	N/m^2			
SI 1Pa	**= 0,102**	**mmH_2O**			
SI 1Pa	**= 100**	**mbar**			
SI 1 bar	= 10^5	Pa			
SI 1 bar	= 10^6	dyn/cm^2			
SI 1 bar	= 10196	mmH_2O			
SI 1 bar	= 1,02	at			
S1 1 bar	= 100	kN/m^2			
SI 1 mbar	**= 10,2**	**mmH_2O**			
1 at	= 10	mH_2O			
1 at	= 1	kp/cm^2 *(kgf/cm^2)*			
1 at	= 98067	Pa (N/m^2)			
1 at	= 736	Torr			
1 atm	= 760	mmHg	1 lbf/in^2 *	= 0,070	kgf/cm^2
1 atm	= 1,033	kgf/cm^2	1 lbf/in^2	= 6895	Pa
1 atm	= 101325	Pa (N/m^2)	1 lbf/in^2	= 0,068	atm
1 atm	= 14,7	lbf /in^2	1 lbf/ft^2	= 4,88	kgf/m^2
			1 lbf/ft^2	= 47,88	Pa
1 kgf/cm^2	= 14,22	lbf/in^2 *(p.s.i.)*	1 $tonf/in^2$	= 15,44	MPa
1 kp/m^2	= 9,81	Pa (N/m^2)	1 $tonf/in^2$	= 2240	lbf/in^2
1 mmH_2O	**= 9,81**	**Pa (N/m^2)**			
			1 inH_2O *(inWg)*	= 25,4	mmH_2O
1 mmHg	**= 13,6**	**mmH_2O**			
1 mmHg	= 133,3	Pa (N/m^2)			
1 torr	= 133,3	Pa (N/m^2)	*(* lbf/in^2 = Pound – force per square inch)*		

Length

SI 1 km	= 0,621	mile	1 mile	= 1,609	km
SI 1 m	= 1,094	yd	1 yard = 3 ft	= 0,914	m
SI 1 m	= 3,281	ft	1 foot = 12 inches	= 0,305	m
SI 1 mm	= 0,0394	inch	1 in	= 25,4	mm
			1 ft	= 304,8	mm
SI 1 μm	= 1	mm			

Area

SI 1 km^2	=	0,386	$mile^2$	1 $mile^2$	=	2,589	km^2
SI 1 m^2	=	1,196	yd^2	1 yd^2	=	0,836	m^2
SI 1 m^2	=	10,76	ft^2	1 ft^2	=	0,0929	m^2
SI 1 cm^2	=	0,155	in^2	1 in^2	=	6,452	cm^2
SI 1 mm^2	=	0,00155	in^2	1 in^2	=	645,2	mm^2

Volume

SI 1 m^3	=	1,308	yd^3	1 yd^3	=	0,765	m^3
SI 1 m^3	=	35,32	ft^3	1 ft^3	=	0,0283	m^3
SI 1 m^3/h	=	0,589	ft^3/min	1 ft^3/min	=	1,698	m^3/h
SI 1 l (litre)	=	0,353	ft^3	1 ft^3	=	28,23	l (litre)
SI 1 l (litre)	=	0,220	Imp. gallon	1 Imp. gal	=	4,546	l (litre)
SI 1 l (litre)	=	0,264	U.S. gallon	1 U.S. gal	=	3,785	U.S. gal
SI 1 dm^3	=	1	1 (litre)	1 bbl* (US)	=	159,0	dm^3
SI 1 dm^3 (oil etc.)	=	$6{,}3 \times 10^{-3}$	bbl (US)	1 bbl (US)	=	35,0	Imp. gal
				1 bbl (US)	=	42,0	U.S. gal
1 dm^3 (dry)	=	$8{,}6 \times 10^{3}$	bbl (US)	1 bbl dry (US)	=	115,6	dm^3
				(bbl = barrel dry)*			

Weight

SI 1 Mg	=	1	t				
1 t	=	1,102	short ton (US)	1 sh. t (US)	=	0,907	t
				1 sh. t.	=	2000	lb
1 t	=	0,984	long ton (UK)	1 long t (UK)	=	1,016	t
				1 long t	=	2240	lb
1 t	=	2205	lb				
SI 1 kg	=	2,205	lb	1 lb	=	0,454	kg
				1 lb	=	16	oz
				1 lb	=	7000	gram
SI 1 kg	=	0,020	cwt *	1 cwt (UK)	=	50,8	kg
				1 cwt (UK)	=	112	lb
				1 sh. cwt (US)	=	45,4	kg
				1 sh. cwt (US)	=	100	lb
SI 1 kg	=	0,0059	bbl	1 bbl (US)	=	170,5	kg
				1 bbl (US)	=	376	lb
SI 1 kg	=	0,035	oz	1 oz (ounce)	=	28,35	g
				1 oz	=	437,5	gr
SI 1 kg	=	15,43	gr	1 gr (grain)	=	64,8	mg
				1 gr	=	1/7000	lb
*(* cwt = hundred weight)*							

POWER

1 N (Newton)	= 0,102 kg – force (kgf)		
1 J (Joule)	= 1 W $\times$ s (N$\times$ m)	1 kpm	= 9,81 J (N $\times$ m)
1 kp	= 9,81 N(kgm/s^2)	1 kp/cm^2	= 0,0981 N/m^2
1 kpm/s	= 9,81 W	1 lfb	= 4,45 N
1 Hp (metric)	= 75 kgfm/s	1 Hp (electric)	= 74 kgfm/s
1 Hp (metric)	= 0,736 kW	1 Hp (electric)	= 0,746 kW
1 Hp (metric)	= 736 W	1 Hp (electric)	= 746 W
1 Hp (metric)	= 0,986 Hp (electric)		
1 W	= 1 J/S (Nm/s)	1 kWh	= 3,6 $\times$ 10^6 J
1 kW	1,34 Hp (electric)	1 kWh	= 3,6 $\times$ 10^5 kpm
1 kWh	= 860 kcal	1 kWh	= 3413 BTU

HEAT

1 J (Joule)	= 1 N $\times$ m (W $\times$ s)		
1 J	= 0,239 cal		
1 cal	= 4,186 J	1 therm	= 10^5 BTU
1 kcal	= 4,186 kJ	1 BTU	= 1055 J(Joule)
1 kcal	= 3,97 BTU	1 BTU	= 0,252 kcal
1 kcal/kg	= 1,80 BTU / lb	1 BTU / lb	= 0,556 kcal/kg
1 kcal/m^2	= 0,369 BTU / ft^2	1 BTU / ft^2	= 2,7 kcal/m^2
1 kcal/m^3	= 0,112 BTU / ft^3	1 BTU / ft^3	= 8,90 kcal/m^3
1 kcal/m^2 $\times$ h $\times$ ^{o}C	= 0,205 BTU/ ft^2 $\times$ h $\times$ ^{o}F	1 BTU/ ft^2 $\times$ h $\times$ ^{o}F	= 4,88 kcal/m^2 $\times$ h $\times$ ^{o}C
1 kcal/m^2 $\times$ h	= 0,369 BTU / ft^2 $\times$ h	1 BTU / ft^2 $\times$ h	= 2,713 kcal/m^2 $\times$ h
1 kcal/m $\times$ h $\times$ ^{o}C	= 8,06 BTU/ ft^2 $\times$ h $\times$ ^{o}F x in	1 BTU/ ft^2 $\times$ h $\times$ ^{o}F x in	= 0,124 kcal/m $\times$ h $\times$ ^{o}C

Temperature

^{0}C	= 5/9 (^{o}F – 32)	^{o}F	= 9/5 ^{o}C +32
100 ^{0}C	= 212 ^{o}F		
0 ^{0}C	= 32 ^{o}F		
SI x ^{o}C	= (X + 273)^{0}K	X^{o}K	= (X – 273) ^{o}C

ASTM E11 #			Tyler *	ISO 565		BS 410 #	
1987			1910	1987		1986	
Nominal Sieve Opening		Seive Designation	Holes per inch				wire diameter
mm	inch	No.	Mesh #	mm	? m	mm	mm
0,005				0,005	5		
0,010				0,010	10		
0,016				0,016	16		
0,020	0,0008	635	635	0,020	20		
0,025	0,0010	500	500	0,025	25		
0,032	0,0012	450	450	0,032	32	0,032	0,028
0,038	0,0015	400	400	0,038	38	0,038	0,03
0,045	0,0017	325	325	0,045	45	0,045	0,03
0,053	0,0021	270	270	0,053	53	0,053	0,04
0,063	0,0025	230	230	0,063	63	0,063	0,05
0,075	0,0029	200	200	0,075	75	0,075	0,05
0,090	0,0035	170	170	0,090	90	0,090	0,06
0,106	0,0041	140	150	0,106	106	0,106	0,07
0,125	0,0049	120	115	0,125	125	0,125	0,09
0,159	0,0059	100	100	0,159	159	0,159	0,10
0,180	0,007	80	80	0,180	180	0,180	0,13
0,212	0,0083	70	65	0,212	212	0,212	0,14
0,250	0,0098	60	60	0,250	250	0,250	0,16
0,300	0,0117	50	48	0,300	300	0,300	0,20
0,355	0,0139	45	42	0,355	355	0,355	0,22
0,425	0,0165	40	35	0,425	425	0,425	0,28
0,500	0,0197	35	32	0,500	500	0,500	0,32
0,600	0,0234	30	28	0,600	600	0,600	0,40
0,710	0,0278	25	24	0,710	710	0,710	0,45
0,850	0,0331	20	20	0,850	850	0,850	0,50
1,000	0,0394	18	16	1,000	1000	1,000	0,56
1,180	0,0469	16	14	1,180	1180	1,180	0,63
1,400	0,0555	14	12	1,400	1400	1,400	0,71
1,700	0,0661	12	10	1,700	1700	1,700	0,80
2,000	0,0787	10	9	2,000	2000	2,000	0,90

ASTM E11 #			Tyler *	ISO 565	BS 410 #	
1987			1910	1987	1986	
Nominal sieve Opening		Sieve Designation	Holes per inch			Wire dia.
mm	inch	No.	Mesh #	mm	mm	mm
2,00	0,787	10	9	2	2	0,90
2,36	0,0937	8	8	2,36	2,36	1,00
2,80	0,110	7	7	2,8	2,8	1,12
3,35	0,132	6	6	3,35	3,35	1,25
4,00	0,157	5	5	4,00	4,00	1,40
4,75	0,187	4	4	4,75	4,75	1,6
5,60	0,223	3,5	3½	5,60	5,60	1,6
6,30	0,250	¼”				
6,70	0,265	0,265”	3	6,70	6,70	1,8
8,0	0,312	5/16”	2,5	8,00	8,00	2,00
9,5	0,375	3/8”	0,371”	9,50	9,50	2,24
11,2	0,438	7/16”	1,441”	11,2	11,2	2,5
12,5	0,500	½”				
13,2	0,530	0,53”	0,525”	13,2	13,2	2,80
16,0	0,625	5/8”	0,624”	16,0	16,0	3,15
19,0	0,750	¾”	0,742”	19,0		
22,4	0,875	7/8”	0,883”	22,4		
25,0	1,00	1”				
26,5	1,06	1,06”	1,05”	26,5		
31,5	1,25	1,25”		31,5		
37,5	1,50	1,50”	1,48”	37,0		
45,0	1,75	1,75”		45,0		
50,0	2,00	2”	2,10”			
53,0	2,12	2,12”		53,0		
63,0	2,50	2,50”		63,0		
75,0	3,00	3”	2,97”	75,0		
90,0	3,50	3,50”		90,0		
100	4,0	4”				
106	4,14	4,14”		106		
125	5,00	5”		125		

	Chart	Page
FLSMIDTH	Clinker particle size distribution	N-1

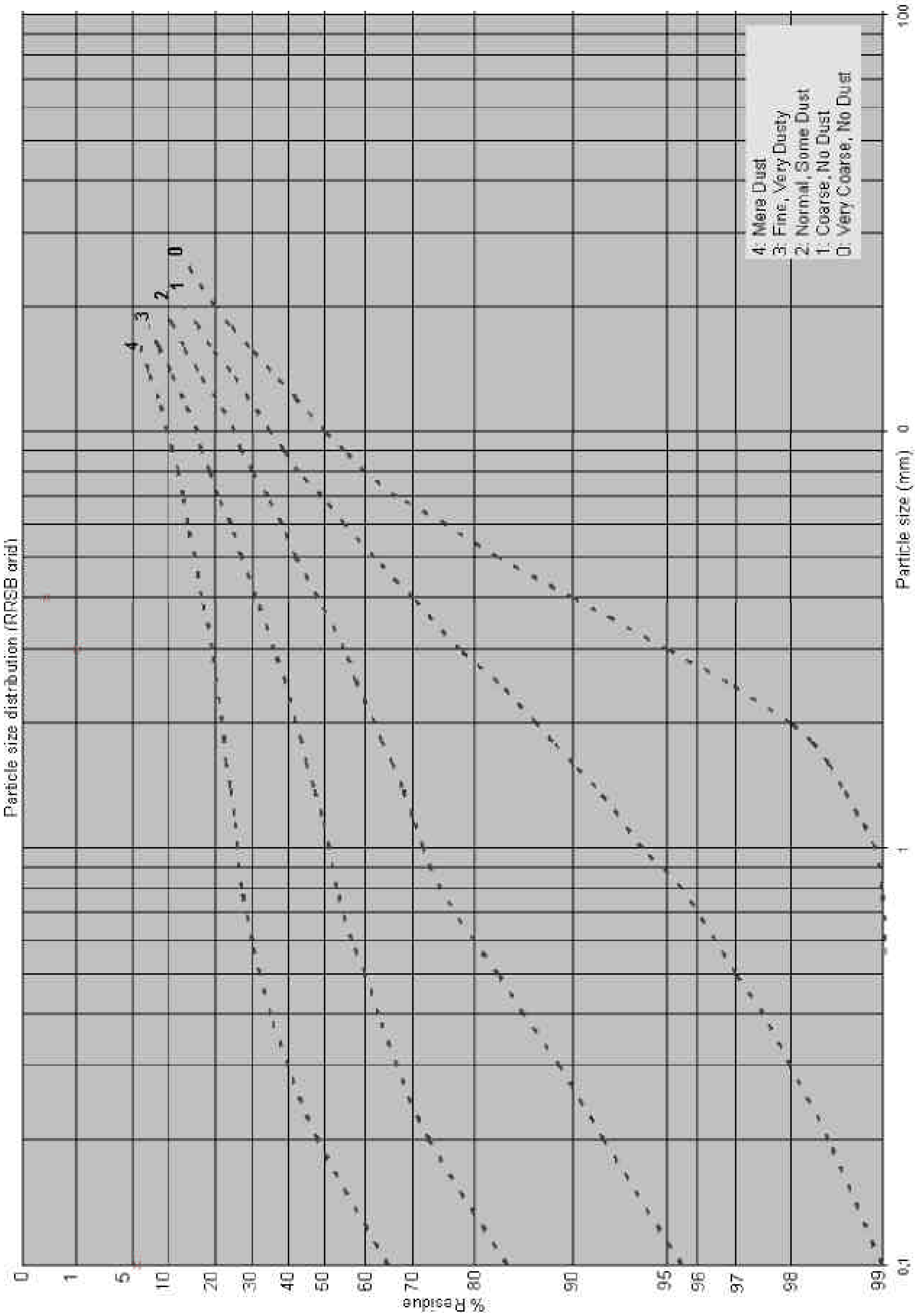
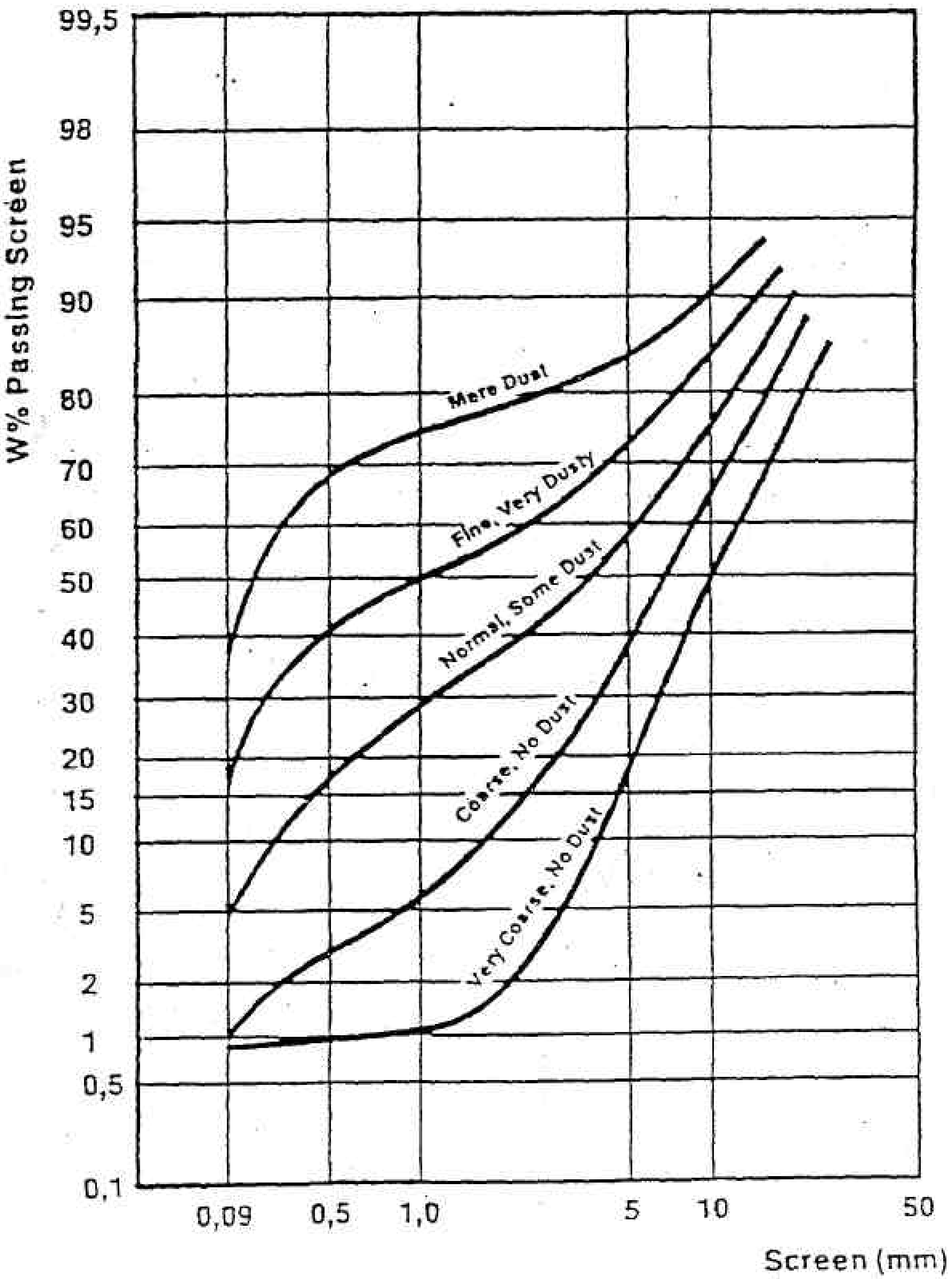
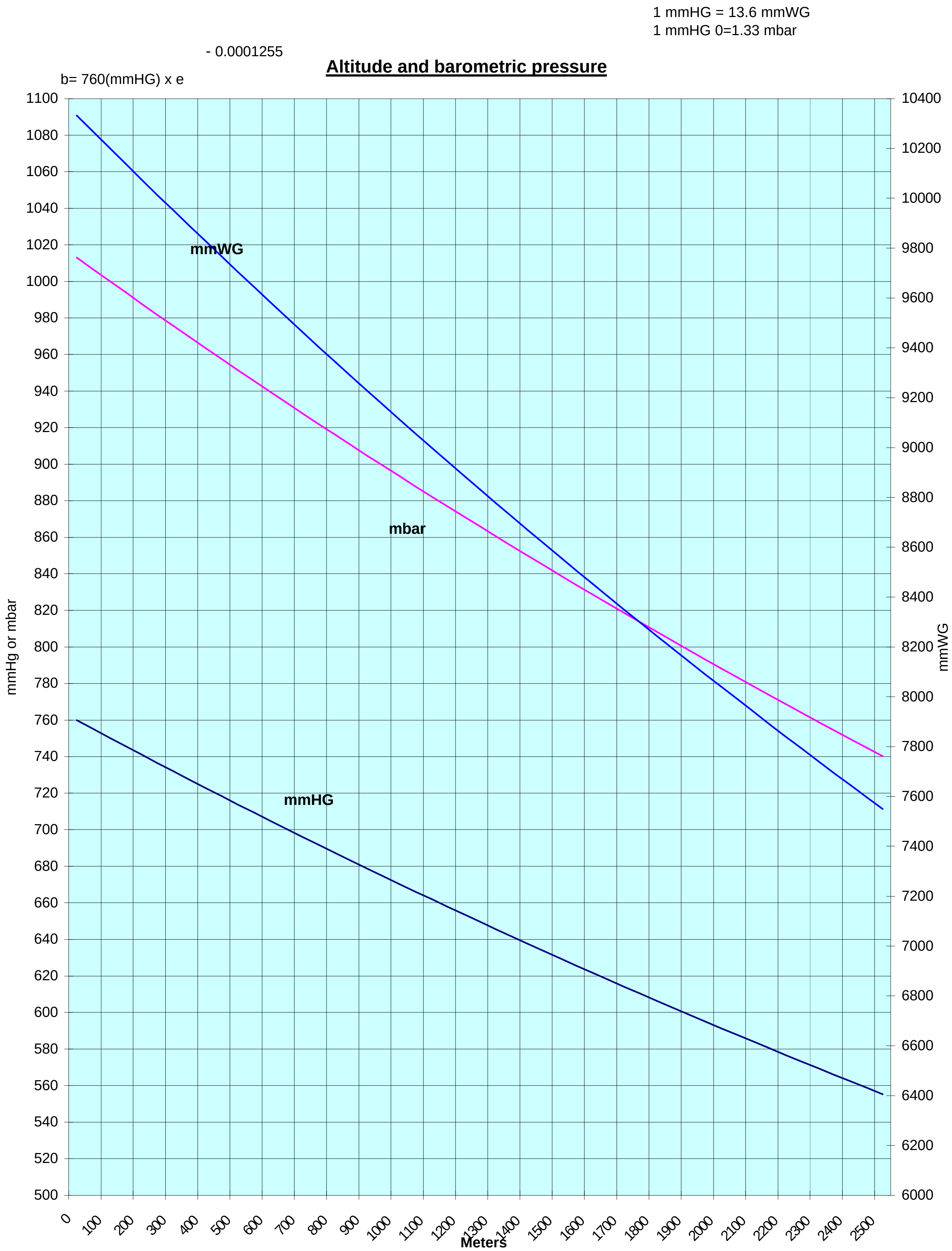


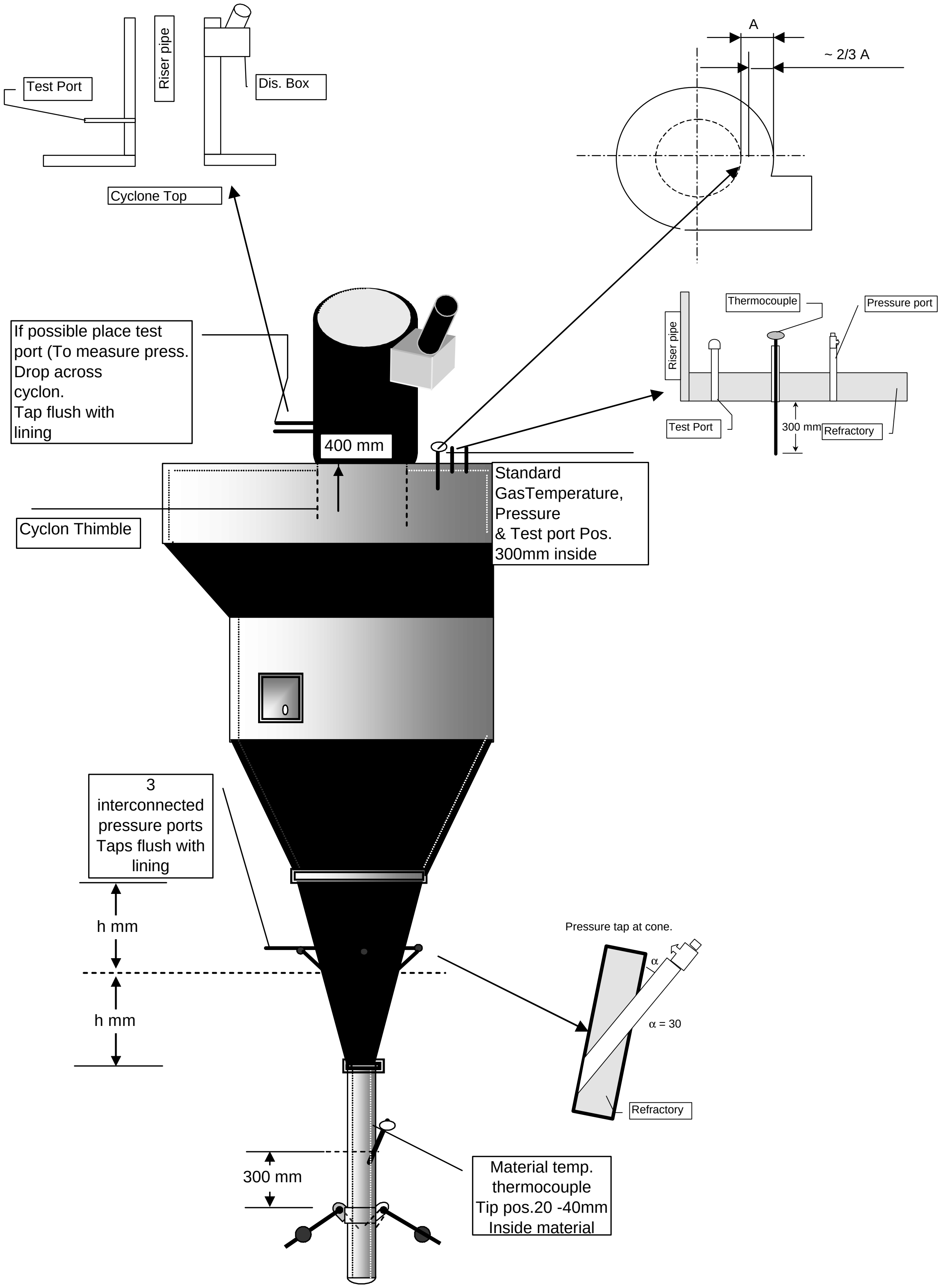
	Chart	Page
	Clinker Partical Size Distribution	N-1



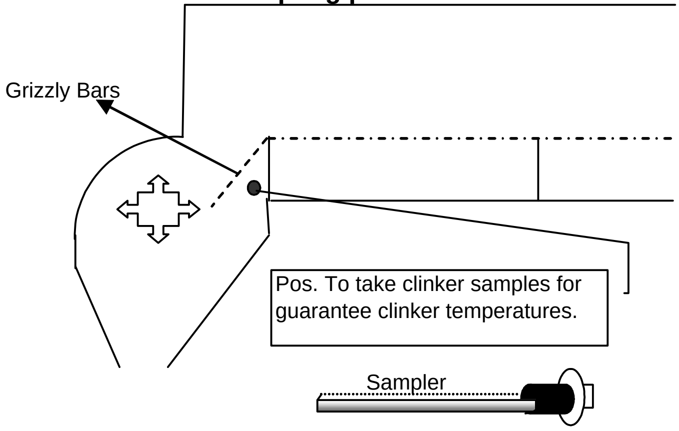
FLSmidth	Chart	Page
	Altitude and barometric pressure	N-2



	Measuring Points	**Page**
	Cyclone	**O-1**



Clinker sampling point on cooler with Hammer crusher



Clinker sampling point on cooler with Roller crusher